Enhancing Integrated Energy and Transport Modelling for the Scandinavian Region

Salvucci, Raffaele

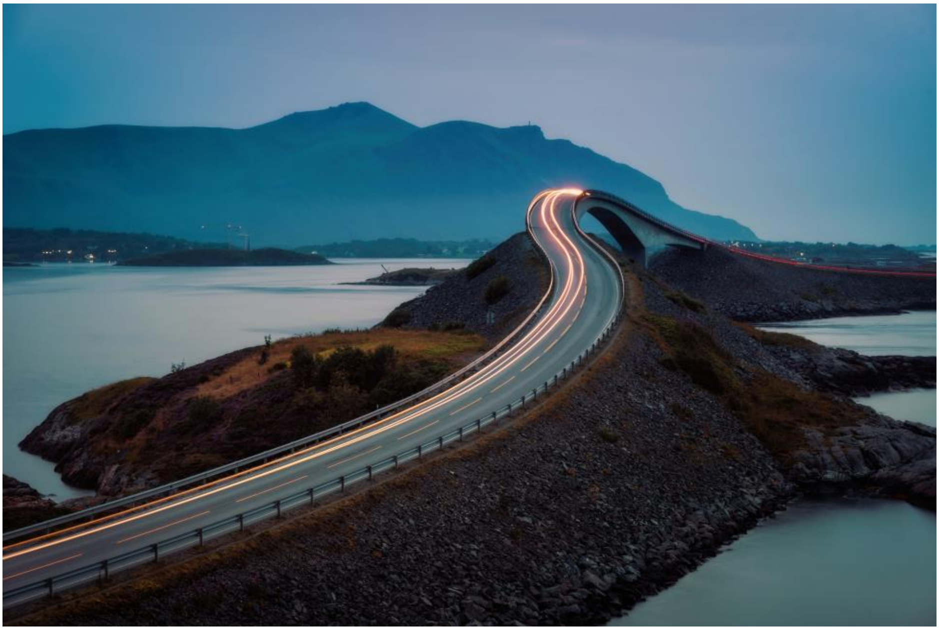
Publication date:
2019

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Salvucci, R. (2019). *Enhancing Integrated Energy and Transport Modelling for the Scandinavian Region*.

Enhancing Integrated Energy and Transport Modelling for the Scandinavian Region



Raffaele Salvucci

PhD Thesis

November 2019

DTU Management

Department of Technology, Management and Economics

Title: Enhancing Integrated Energy and Transport Modelling for the Scandinavian Region
Type: PhD thesis
Date: 08 November 2019

Author: Raffaele Salvucci

Main supervisor: Prior: Senior researcher Kenneth Karlsson
Current: Professor Russell McKenna
Co-supervisors: Eng. Maurizio Gargiulo and senior researcher Tanu Priya Uteng

University: Technical University of Denmark
Department: DTU Management Engineering
Division: Sustainability
Address: Produktionstorvet Building 424

DK-2800 Kgs. Lyngby
www.man.dtu.dk

SUMMARY

Transportation has always been an essential activity for human society, but, is also responsible for several externalities. Today the transport sector accounts for almost one-third of final energy demand and for approximately one-third of global energy-related CO_2 emissions. Changing the current transport paradigm is crucial to meet global environmental goals such as the Paris Agreement, though this requires a broad set of technological and behavioural measures summarized in the International Energy Agency (IEA) slogan Avoid, Shift, Improve. Nordic countries are pioneers in deploying sustainable energy technologies, as witnessed by the wide penetration of renewables in the power and heat sectors. However, the transport sector lags behind, representing the largest source of Nordic greenhouse-gas (GHG) emissions and accounting for 40% of total CO_2 emissions, a higher share compared to the global average. A low-carbon transition of the Nordic transport sector has slowly started. Indeed, the Nordic region represents the third largest electric car market by volume of sales in the world. However, further mitigation measures and a solid decarbonisation strategy encompassing all the sub-sectors (including navigation and aviation) are needed. Relying on a rich and diversified portfolio of renewable energy sources and expertise, Nordic countries could benefit by outlining a common mitigation strategy by embracing a larger variety of sustainable solutions and possible synergies. Energy system models have been applied for more than three decades to investigate sustainable pathways to meet energy and environmental goals for specific sectors or even for the whole energy systems. In particular, bottom-up (BU) optimization energy-economy-environmental-engineering (E4) models provide a thorough technological description besides considering cross-sectorial and cross-regional dynamics and synergies. Though, these models are generally weak in representing human behaviour, an important aspect in transport decision making.

This PhD thesis builds on the research field of energy systems analysis to enhance integrated energy and transport modelling aimed at robust planning for the decarbonisation of the Scandinavian transport sector. A systematic critical review of studies applying energy system analysis for integrated energy and transport scenarios for the Nordic region lays the basis for this work. Research gaps and potential modelling improvements are identified in light of recent findings in transport research and considering the future challenges that the

sustainable transition of the transport sector is likely to face. Such limitations are tackled by this PhD thesis through two main scientific contributions. The first contribution addresses a weakness of BU optimization E4 models: the poor representation of transport modal competition. A novel methodology enabling transport modal shift through the application of substitution elasticities is developed to tackle this gap. For the passenger sub-sector, this represents an attempt to enhance the weak capability of BU optimization E4 models to depict transport behavioural dimensions. The methodology is tested and applied for a real case study to investigate the role of modal shift in decarbonising the future Scandinavian transport sector under an increasing CO_2 tax. Transport modal shift, towards the more efficient and less carbon-intense modes (e.g. rail), results a cost-effective measure to reduce cumulative CO_2 emissions. The presented methodology facilitates more comprehensive analyses by enabling a wider range of applications compared to traditional approaches. For instance, the Shift pillar at the base of the IEA decarbonisation strategy can be integrated directly in the analysis. In addition, endogenous modal shift is enabled for both passengers and freight, representing further progress compared to previous attempts in BU optimization E4 models, which focus mainly on passengers.

The second contribution to tackle the gaps identified is the development of an open-source energy system model (TIMES-Nordic) depicting the full Scandinavian energy system. TIMES-Nordic structure is designed to overcome most of the modelling limitations identified in the reviewed literature. Besides including elastic modal shift, the model is enriched by breakthrough energy and transport technologies and innovative fuel chains. The full energy system of each country is modelled separately, allowing the investigation of sustainable pathways for the whole Scandinavian region while enabling the identification of specific national strategies. All sectors composing the national energy systems are included, enabling resource competition and technological synergies to be identified across sectors. All transport sub-sectors (including international aviation and navigation) are modelled to provide a complete outlook for emission reduction strategies. Concluding, this PhD thesis provides tools (open-source) and methodologies that can support fellow researchers and modellers interested in the decarbonisation of the Scandinavian transport sector. Concerning suggestions for further research, substitution elasticities could be tested to describe other phenomena than transport modal shift, while TIMES-Nordic can be further developed to address the remaining modelling gaps.

RESUMÉ (DANISH)

Transport har altid været en vigtig aktivitet i vores samfund, men er også ansvarlig for flere eksternaliteter. I dag står transportsektoren for næsten en tredje del af det samlede energiforbrug og for omkring en tredje del af de globale energi-relaterede CO_2 emissioner. Det er derfor vigtigt at ændre den nuværende transportsektor for at opnå de globale klima og miljø mål, som, for eksempel, er sat i Paris Aftalen. Denne omstilling kræver et bredt spektre af teknologi og adfærd bestemte foranstaltninger, som kan blive opsummeret i sloganet ”Undgå, Skift, Forbedre”, fra det Internationale Energiagentur (IEA). De nordiske lande er pionerer i at implementere bæredygtige energiteknologier i energisystemet, hvor høje andele af vedværende energikilder allerede benyttes i elektricitet- og varme-sektorerne. Transportsektoren halter imidlertid bagud, og står for den højeste andel af de nordiske drivhusgasudledninger med omkring 40% af de samlede CO_2 udledninger, hvilket er en højere andel end det globale gennemsnit. En grøn omstilling af den nordiske transportsektor er langsomt begyndt. Den nordiske region repræsenterer det tredje største elbil marked i verden, baseret på antallet af solgte elbiler. Der er derfor et behov for en solid strategi for den grønne omstilling, der omfatter alle delsektorer (inklusiv navigation og luftfart). Den nordiske region har et rigt og diversificeret portefølje af vedvarende energikilder samt ekspertise. Med dette som grundlag, kan det være fordelagtigt for de nordiske lande at fremlægge en samlede strategi, som omfatter de store variationer af bæredygtige løsninger og mulige synergier i den nordiske region. Energisystemmodeller er igennem mere end tre årtier blevet benyttet til at undersøge bæredygtige energiscenarier, som opnår energi og klima-målene for specifikke sektorer og for hele energisystemer. Især bottom-up (BU) (E4) optimeringsmodeller, som inkluderer og kombinerer energi-økonomi-miljø-ingeniør områder benyttes til at analysere fremtidige energisystemer grundet deres dybdegående beskrivelse af teknologier i det samlede energisystem, hvor også de komplicerede dynamikker og synergier på tværs af sektorer og regioner inddrages som led i optimeringen. På trods af de mange positive funktioner er disse modeller generelt svage i deres repræsentation af menneskelig adfærd, hvilket er et vigtigt aspekt når beslutninger i transportsektoren træffes.

Denne PhD afhandling bidrager til forskningsområdet inden for energisystemanalyse, ved at forbedre modelleringen af den integreret energi og transport

system, med det formål, at udforme robuste scenarier for den grønne omstilling af den skandinaviske transportsektor. Som basis for dette arbejde er et systematiske og kritisk litteraturstudie blevet lavet, som undersøger scenarier for integreret nordiske energi og transport systemer. Fra dette studie blev forskningshuller og potentielle forbedringsmuligheder for energisystemmodellering identificeret. Dette blev identificeret i lyset af de nyeste resultater inden for forskning i transportsektoren samt ved at tage fremtidige udfordringer for den bæredygtige omstilling af transportsektoren med i betragtning. Baseret på konklusionerne fra dette litteraturstudie, har denne PhD afhandling to hovedbidrag. Det første bidrag adresserer en svaghed i BU E4 optimeringsmodeller: nemlig den svage repræsentation af konkurrencen mellem transportmidler. For at imødekomme dette blev der udviklet en ny metode til at modellere modale skift i transportsektoren, ved at benytte konceptet vedrørende substitution elasitet. Inden for passager transporten bidrager den nye metode med et forsøg på at forbedre den svage repræsentation af adfærdsdimensioner i transport sektoren for BU E4 modeller. Den nye metode er testet og anvendt i et studie til at undersøge hvilken rolle modale skift har i den fremtidige skandinaviske transportsektor, hvor CO_2 skatten stiger. Modale skift i transportsektoren, mod mere effektive og mindre klima-intense transportmidler (for eksempel, jernbane) resulterer i en omkostningseffektiv måde at reducere de samlede CO_2 udledninger. Den nye metode faciliterer mere omfattende analyser ved at tillade a bredere vifte af applikationer i forhold til de mere traditionelle metoder. For eksempel, kan ”Skift” begrebet fra IEA sloganet nu blive integreret direkte i analyserne af transportsektoren. I tillæg er modal skift både for passager og fragt transport optimeret i modellen, hvilket er et yderligere bidrag i forhold til tidligere forsøg i BU E4 optimerings modeller, som fokuserede mere på passager transport.

Det andet forskningsbidrag i denne PhD afhandling er udviklingen af den open-source energisystemmodel (TIMES-Nordic) som omfatter det komplette skandinaviske energisystem. Strukturen i TIMES-Nordic er designet til at imødekomme de fleste af de modelbegrænsninger som blev identificeret i litteraturstudiet. Udover at inkludere elastisk modale skift i transportsektoren, så er modellen beriget med nye energi og transport teknologier samt innovative teknologier til brændselsproduktion. Det komplette energisystem er modelleret for hvert land, hvilket tillader analyser af bæredygtige omstillingsscenarier for den samlede skandinaviske region, mens specifikke nationale strategier samtidig er repræsenteret. Alle sektorer i det nationale energisystem er inkluderet, hvilket tillader analyser af konkurrencen om energi ressourcer samt teknologiske synergier på tværs af energisektorerne. Alle delsektorer (herunder international fly og navigations transport) er modelleret for at give et komplet billede af strategier for at imødekomme energi og klima-mål i transport og energisektoren. Som konklusion, så biddrage denne PhD afhandling med at levere en energisystemmodel (open-source) og nye metoder, der kan supporte andre forskere og modelfolk som er interesseret i den fremtidige grønne omstilling af den skandinaviske transportsektor. Som forslag til yderligere forskning, så kan substitutions elastisitet blive testet for at beskrive andre fænomener end modale skift i transportsektoren, hvor TIMES-Nordic kan blive udviklet yderligere til at undersøge andre resterende forskningehuller inden for energisystem modellering.

PREFACE

The work presented in this PhD thesis was conducted from May 2016 to November 2019 at the Department of Management Engineering of the Technical University of Denmark (DTU) under the supervision of senior researcher Kenneth Karlsson (prior) and of Professor Russell McKenna (after). The co-supervision was carried out by Eng. Maurizio Gargiulo from E4SMA ltd and senior researcher Tanu Priya Uteng from the Norwegian Centre for Transport Research (TØI).

The PhD project was part of the SHIFT - Sustainable Horizons in Future Transport project funded by the Nordic Energy Research (NER) (grant number 77892). SHIFT was led by the Swedish Environmental Research Institute (IVL) in collaboration with the Technical University of Denmark (DTU), the Institute of Transport Economics (TØI) and Viktoria Swedish ICT.

In addition, the PhD student spent four months for his external research period at the Department of Energy (DENERG) of Politecnico di Torino (March 2018 – June 2018), under the supervision of Prof. Stefano Corgnati.

This PhD thesis is based on three scientific journal papers and a book chapter prepared in collaboration with internal and external partners. These publications are referred to by Roman numerals (**I-IV**) throughout the thesis.

I. Salvucci R, Tattini J. (2019). Global outlook for the transport sector in energy scenarios. In: Andersen K, Jørgensen B, Nielsen O, editors. DTU International Energy Report 2019 – Transforming Urban Mobility.

II. Salvucci R, Petrović S, Karlsson K, Wråke M, Uteng TP, Balyk O. (2019) Energy Scenario Analysis for the Nordic Transport Sector: A Critical Review. *Energies*, 12 (12). DOI: 10.3390/en12122232

III. Salvucci R, Tattini J, Gargiulo M, Lehtilä A, Karlsson K. (2018) Modelling transport modal shift in TIMES models through elasticities of substitution. *Applied Energy*, 232, 740-751. DOI: 10.1016/j.apenergy.2018.09.083

IV. Salvucci R, Gargiulo M, Karlsson K. (2019) The role of modal shift in decarbonising the Scandinavian transport sector: Applying substitution elasticities in TIMES-Nordic. *Applied Energy*, 253. DOI: 10.1016/j.apenergy.2019.113593

ACKNOWLEDGEMENTS

This PhD thesis is the product of a long journey, which has been possible thanks to the support of many people.

First of all, I would like to thank my supervisor Kenneth Karlsson, for inspiring me during this long adventure and providing me with a true example of commitment to fight climate changes. Thank you Kenneth! I also wish to thank my co-supervisor Maurizio Gargiulo for providing me with strong modelling support and very precious advice. Thank you Maurizio for having shared your knowledge with me. Thanks also to my co-supervisor Tanu Priya Uteng, who has shared all her transport expertise (and data) with me. Last but not least, a special thank goes also to Professor Russell McKenna, who has taken care of my supervision during the last month of my PhD.

I also want to thank all the co-authors of the manuscripts included in this thesis, among who a heartfelt hug goes to Jacopo for the prolific exchange on the topic and the many energy adventures spent together. A special thank goes also to the Energy System Analysis group, a family, which I had the chance to join since February 2015. Thanks for having enriched my working hours with interesting conversations and a creative environment. Moreover, thank you, Stefan and Valentina, for having been my third and fourth informal co-supervisors.

I also would like to thank Professor Stefano Corgnati and Professor Romano Borchiellini for giving me the opportunity to visit for a research period the Energy Center of the Politecnico di Torino, which has also been possible thanks to the financial support of the Otto Mønsteds Fond.

A grateful thank goes to my family and friends in Florence, whose support and love has been essential for the finalization of this PhD. A special thank goes to Mara and Donato, who brought me on this planet, to Nonna Margherita and Zia Ornella who always welcome me in Fiesole as if I never left my town and to my brother Marco and his girlfriend Chiara who don’t miss an opportunity to bring me around and enjoy life. Moreover, a special mention goes to Matero for the therapeutic phone correspondence, to Lore (il Guerriero della Luce) for his eclectic life insights and to Zuri for the wine.

Last but not least, I want to tighten with a huge brotherly hug all the Blue House & friends: Karis, Paolo, Giovanna, Monica, Louise, Giuppo, Cornelius, Bob, Ruth, Greg, Rosa, Anthéa, Gabriele, Lisa, Fede, Simo, Manos and David. These guys have been preparing dinner for me almost every day during last year, feeding me with laughs and light-heartedness, the most needed nutrients during a PhD. Thank you guys for putting up with me for so long ☺.

“There's so many different worlds
So many different suns
And we have just one world
But we live in different ones”

Extracted from “Bothers in Arms”, Mark Knopfler, Dire Straits, 1982.

ABBREVIATIONS

4DS	4 Degree Scenario
BE	Battery electric
BECCS	Bio-energy with carbon capture storage
BEV	Battery electric vehicle
BU	Bottom-up
BY	Base year
CCS	Carbon capture and storage
CES	Constant elasticity of substitution
CI	Carbon intensity
CNS	Carbon Neutral Scenario
CO_2	Carbon dioxide
CORSIA	Carbon Offsetting and Reducing Scheme for International Aviation
E4	Energy-economy-environmental-engineering
EEDI	Energy Efficiency Design Index
ETP	Energy Technology Perspectives
ETSAP	Energy Technology Systems Analysis Programme
EV	Electric vehicle
Flex4RES	Flexibility for Variable Renewable Energy Integration in the Nordic Energy Systems
GDP	Gross domestic product
GHG	Greenhouse-gas
H	Hybrid
I	International
IEA	International Energy Agency
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
IMO	International Maritime Organization
ITS	Intelligent transport systems
J	Joule
L	Long
LoS	Level of Service
LP	Linear program
M	Medium
MaaS	Mobility as a Service

MNL	Multinomial logit
MoMo	Mobility Model
NDCs	National Determined Contributions
NER	Nordic Energy Research
NETP	Nordic Energy Technology Perspectives
NL	National long
NOx	Nitrogen oxides
NPS	New Policies Scenario
NS	National short
PHEV	Plug-in hybrid vehicle
Pkm	Passenger-kilometres
PVF	Net present value factor
S	Short
SDS	Sustainable Development Scenario
SHIFT	Sustainable Horizons in Future Transport
SO_2	Sulphur dioxide
TD	Top-down
TIMES	The Integrated MARKAL-EFOM System
Tkm	Tonne-kilometres
TP	Travel pattern
WTT	Well-to-tank
WTW	Well-to-wheel
XS	Extra short

List of contents

1 INTRODUCTION

The introduction of this PhD thesis is articulated as follows: in Section 1.1 the background and motivation are presented (partially based on Paper **III** and **IV**), in Section 1.2, the research questions are formulated, while Section 1.3 presents the outline of the thesis.

1.1 BACKGROUND AND MOTIVATION

Transportation is and has always been an essential activity for the human society. The movement of goods and people across distances represents a key enabler of economic and social development. However, transport is an energy intense activity, which has special needs. In the majority of cases, the source of energy employed has to be transportable, thus, it needs to be stable under standard conditions and its energy density has to be high enough to be stored in a compact way. Historically, this role has been played by oil products, which have dominated the scene for the last century due to the advent of the internal combustion engine. Despite the human progress in science and technology, which have drastically improved the performances and energy economy of transport means, oil products still cover 93% of today's transport total final energy consumption worldwide [1]. In addition, transportation represents almost one third of global final energy consumption and is responsible for approximately 23% of energy-related CO_2 emissions [2]. Moreover, transport emissions increased by 2.5% annually between 2010 and 2015 [3], due to the increase in transport activity. In fact, transport demand is tightly coupled with gross domestic product (GDP), income and population levels, which are growing factors in many areas of the globe (especially developing countries) [2]. These are only few reasons why the transport sector is widely consider the most complicated sector to decarbonise. Indeed, low-carbon transport technologies are already available in the market but their adoption is hampered by the high costs, which call for policy support [4,5]. In addition, the slow turnover rate of the existing vehicle stock and infrastructure limit the penetration of new technologies. These challenges call for serious actions and mitigation measures as a result of the increased awareness of climate changes [6]. In the baseline scenario of the Energy Technology Perspectives (ETP), the International Energy Agency (IEA) estimates that by 2050 global transport energy consumption will increase by 75%, with a concomitant doubling of associated CO_2

emissions [7]. The IEA suggests a combination of technological and behavioural measures to be promoted concurrently for a low-carbon transition of the transport sector: avoiding travel, shifting to different modes, improving vehicle efficiency and switching to low-carbon fuels [8,9].

Until now, efforts to reduce emissions through technology improvements and fuel standards have been levelled by the activity increase [2]. Moreover, countries have recently announced policy ambitions and commitments in their National Determined Contributions (NDCs) under the Paris Agreement [10], though such measures are still not sufficient to limit the average increase in temperature to “well below 2 degrees” above pre-industrial levels, as assessed by [11] and reflected in the New Policy Scenario outlined by the IEA [12].

In the Nordic region, the transport sector represents the greatest source of green-house gasses (GHGs). It accounts for almost 40% of total energy-related CO_2 emissions [13], which is higher than the global average (23%, [3]). However, the Nordic countries are pioneers in deploying sustainable energy technologies, each with its peculiarities: e.g. wind power in Denmark, hydropower in Norway, biomass in Finland and Sweden and geothermal energy in Iceland. Moreover, the well-integrated Nordic regional electricity market is enabling a high penetration of renewables, for instance connecting Norwegian hydro reservoirs to Danish wind farms in periods with a lack of demand. Beside the power and heat sector, the Nordic transport sector has also started a slow sustainable transition. For instance, the aggressive policy support for electric cars (especially in Norway) has recently made the Nordic region the third largest electric car market by volume of sales in the world, just after China and the United States [4]. However, the Nordic transport sector is still far from decarbonisation.

Relying on a rich portfolio of diversified renewable energy sources and expertise, Nordic countries could benefit by outlining common mitigation strategies by embracing a larger variety of sustainable solutions and possible synergies [14]. Indeed, the synergic exploitation of national energy sources, technology expertise and infrastructure could facilitate such low-carbon transition. Moreover, the Nordic region is already today in a favourable position in creating first-mover advantages regarding the low-carbon technological transition [15]. Therefore, besides benefitting from reducing their own emissions, the Nordics could eventually help other European countries in achieving their environmental goals by exporting the developed solutions and expertise.

Energy system models are powerful tools for investigating alternative pathways in energy planning. Such models have been employed for more than three decades to test possible strategies to meet national and global energy and environmental targets aimed at, first and foremost, mitigate climate change [16]. Energy system models provide a test ground for energy policies effectiveness and for their effect on technology deployment while tracking national resources potentials. In particular, bottom-up (BU) optimization energy-economy-environmental-engineering (E4) models rely on a thorough technology description, while embodying the economic and environmental system dimensions. These models are capable of exploring feasible decarbonisation pathways while considering cross-sectorial dynamics and synergies. However, these models are generally weak in depicting important behavioural aspects driving transport dynamics such as modal shift.

Despite the potential benefits in outlining common mitigation strategies across Nordic countries for the decarbonisation of the transport sector, most of the available literature focuses on single countries, while the Nordic region as a whole is not addressed with the same interest [17]. Moreover, besides few exceptions, most of the studies targeting the Nordic or even the Scandinavian region focus on research questions and modelling framework including only part of the transport sector (often road transport) and only a portion of the energy system (e.g. power sector) [17]. Given the growing awareness of the climate change issue, further studies investigating comprehensive mitigation strategies for the whole Nordic or Scandinavian region, are expected and desirable to be pursued. In light of the above, this PhD thesis attempts at screening the actual status of energy scenario analysis for a low-carbon transport sector in the Nordic region to identify research gaps and modelling limitations. Consequently, enhanced modelling solutions and tools are developed and applied to support solid and comprehensive integrated energy and transport modelling for the Scandinavian case.

1.2 PURPOSE OF THE THESIS AND RESEARCH QUESTIONS

This PhD thesis aims at strengthening the role of energy system analysis for strategic decision making and energy planning supporting a low-carbon transition of the Scandinavian transport sector. A particular focus is posed on improving the description of the transport sector in energy system models to enhance the solidity of the results.

The PhD thesis provides a review of studies applying energy system models to tackle scenario analyses for the Nordic transport sector. Research gaps and limitations are identified in the selected literature and solutions to fill them are developed, tested and applied for the Scandinavian case. In particular, a specific focus is dedicated to develop a novel methodology to represent transport modal shift into BU optimization E4 models, which is tested and applied for a real case study (Scandinavian region).

The research questions tackled by this PhD thesis are formulated as follows:

RQ1 What is the global energy outlook of the transport sector? What are the main upcoming challenges with respect to the decarbonisation of the transport sector worldwide?

RQ2 What is the state-of-the art of energy scenario analysis for a low-carbon transition of the Nordic transport sector? What are the research gaps and modelling limitations that call for further research?

RQ3 How can transport modal shift (for both passenger and freight) be modelled in large multi-regional models such as TIMES-Nordic? What are the modelling implications of using substitution elasticities to model transport modal shift in TIMES models?

RQ4 What are the main issues when applying substitution elasticities to model transport modal shift for a real case study? What is the potential role of modal shift in the decarbonisation of the Scandinavian transport sector?

Each of the above research questions has been investigated by one of the paper included in this thesis. The roman numerals used to list the papers in the Preface corresponds to the numbering of the research questions addressed by the manuscript (Table 1.1):

Table 1.1. *Research questions addressed by the papers included in this PhD thesis.*

	Papers			
	I	**II**	**III**	**IV**
RQ1	●			
RQ2		●		
RQ3			●	●
RQ4				●

Besides the above research objectives, an additional important outcome of this PhD work is the development of an open-source BU optimization E4 model depicting the full Scandinavian energy system: TIMES-Nordic, to which the PhD student contributed substantially during the whole duration of his studies.

1.3 THESIS OUTLINE AND SCIENTIFIC CONTRIBUTION

This thesis is articulated in two halves: in the first part the scientific outcomes of the work carried out during the PhD activities are summarised and additional insights (not included in the articles) are provided. In particular, the first part of the thesis is articulated as follows:

Chapter 2 provides the context of the PhD research activities. In particular, energy system analysis as a scientific discipline is briefly presented and the energy outlook of the global transport sector is provided together with the identification of upcoming challenges (and possible mitigation strategies) related to the threat of climate change. Chapter 2 tackles **RQ1** by summarizing the scientific outcome of Paper **I**.

Chapter 3 includes a literature review on energy scenario analysis for the Nordic transport sector, where research gaps and limitations are identified in light of recent findings in transport literature and recommendations are provided. Chapter 3 tackles **RQ2** and is based mainly on Paper **II** and partly on Paper **III**.

Chapter 4 presents TIMES-Nordic, a BU optimization E4 model depicting the full energy system of Scandinavia (Denmark, Norway and Sweden). TIMES-Nordic was developed during this PhD project and it has been one of the main modelling platform supporting this research, indeed, its structure has been directly influenced by the research outcomes of the articles presented in this thesis. Part of its structure has been moulded based on the outcomes of Paper **II**.

Chapter 5 presents a novel methodology to include transport modal shift endogenously in TIMES models by using substitution elasticities. Chapter 5 tackles **RQ3** and it is mainly based on Paper **III.**

Chapter 6 provides a first application of the developed methodology for a real case study. Specifically, modal shift is analysed in terms of its potential role in decarbonising the Scandinavian transport sector under an increasing CO_2 tax. The chapter concludes by critically discussing modelling limitations, data assumptions and outlining possible improvements for both the novel methodology and its first application. Moreover, a few additional analyses aimed at testing the solidity of the obtained results are presented. Chapter 6 tackles **RQ4** and is mainly based on Paper **IV**.

Chapter 7 provides the outlook and conclusions of this PhD work. In particular, the actual status of TIMES-Nordic, including the latest improvements implemented within the SHIFT project, is described and an interactive web-interface to consult most recent results from the SHIFT project is presented. Lastly, suggestions for further research and conclusions are provided.

The second part of the thesis includes a collage of the publications written within the PhD studies (Appendix C). The scientific novelty of each paper is briefly described hereafter, together with its role within the conceptual framework of this thesis.

Paper I: the role of Paper **I** in this thesis is to describe the "burning platform" represented by the current unsustainability of the transport sector and to provide an overview of possible challenges and solutions related to its decarbonization within a global context. Paper I contributes to the scientific literature on the topic by summarizing recent findings, key policy recommendations and by describing results from official scenarios by the IEA.

Paper II: the role of Paper **II** within this PhD thesis is to prepare the scientific ground for the research activities carried out. The scientific contribution to the literature is mainly embodied by the identification of modelling limitations/weaknesses and elements for further research supporting more solid integrated energy and transport analyses for the Scandinavian region.

Paper III: the role of Paper **III** in this thesis and its scientific contribution is to provide a new methodology aimed at overcoming one of the identified modelling gaps. The gap addressed relates to the poor capability of BU optimization E4 models to capture transport modal competition, which for passenger transportation translates into capturing behavioural dynamics related to modal choice, a crucial aspect when addressing mitigation strategies for this sector. The methodology developed is novel and tackles both passenger and freight transportation, while previous attempts focus only on the former, representing a step forward within this research field.

Paper IV: the role of Paper **IV** in this thesis and its contribution to the scientific literature is to provide a first case study analysis of the developed methodology. Besides identifying the transport elasticity type compliant with the adopted modelling framework, it shows the positive contribution of modal shift in supporting a sustainable transition of the Scandinavian transport sector.

Besides the papers drafted, TIMES-Nordic also represents a relevant scientific contribution to the Scandinavian energy modelling community. Indeed its structure and features have been shaped to fill part of the modelling gaps identified in Paper **II**. Therefore, TIMES-Nordic can support fellow researchers and modellers to enrich the Scandinavian energy and transport analyses, by overcoming some of the identified shortcomings.

2 FOUNDATIONS FOR THE DECARBONISATION OF TRANSPORT

The scientific content of this PhD thesis involves the application of energy system models to investigate low-carbon pathways for the Nordic transport sector. The aim of this chapter is:

(i) To briefly illustrate the adoption of energy system models for energy planning and long-term decision making (Section 2.1).

(ii) To provide an overview of: the main challenges related to the decarbonisation of the transport sector that the world is likely to face within the next decades, and of the possible sector-specific measures to mitigate global warming (based on reviewing official scenarios from the International Energy Agency – IEA) (Section 2.2).

Ground knowledge of the energy system analysis paradigm together with the specific needs of the transport sector in tackling reduction in emissions is fundamental for understanding the novel contribution of this work respect to previous attempted frameworks.

2.1 ENERGY SYSTEM ANALYSIS

Energy system models have been supporting long-term decision making for the energy sector for more than three decades and for different countries [16], representing valuable and powerful tools for identifying specific technology deployment pathways under alternative policy scenarios. In particular, BU optimization E4 models stand for their detailed representation of the technological, economic and environmental dimensions of the energy system. BU optimization E4 models have been extensively applied to investigate dedicated decarbonisation strategies for specific sectors such as heat [18], residential [19] and transport [20,21].

In this thesis, a special focus is posed on a specific family of BU optimization E4 models, the TIMES (The Integrated MARKAL-EFOM System) models. These models, besides being applied to analyse single sectors such as electricity and district heat [22], are capable of encompassing the entire energy system, allowing to explore decarbonisation pathways while considering cross-sectoral dynamics and synergies. This characteristic is particularly relevant considering that in the future the transport sector is expected to be progressively more integrated with the rest of the energy system.

The TIMES model generator is developed and maintained by the Energy Technology Systems Analysis Programme (ETSAP) [23], an IEA Technology Collaboration Programme. TIMES models are partial-equilibrium energy system models that assume perfectly competitive markets and full foresight. TIMES models are suitable for medium or long-term future scenario analyses of energy systems ranging from the city level [24] to the national and global levels [25]. TIMES models optimize investments in technologies and their operations over the defined time horizon by minimizing total system costs, while satisfying the exogenous energy service demand curves and respecting user-defined constraints such as environmental targets, resource availability and policy restrictions. Typical inputs to TIMES models are energy service demand curves and the techno-economic parameters of technologies represented, while outputs range from technology investments and operation levels, energy commodities marginal prices to CO_2 emissions and system costs. More information on TIMES models is provided by [22].

TIMES models have been extensively used to identify least-cost resources and technology deployment pathways towards GHG emission-free energy systems, exploring alternative scenarios under several constraints and for different countries, for instance, Ireland [26], California [27,28], Canada [29], China [30], Denmark [31], Norway [32] and Sweden [33].

2.2 GLOBAL TRANSPORT ENERGY OUTLOOK

This section attempts at answering to **RQ1** and is draft based on Paper **I**.

2.2.1 GLOBAL CHALLENGES IN TRANSPORTATION

Given the relevance of transport externalities (Section 1.1), changing the current transport paradigm is of major importance to the tasks of mitigating climate change, alleviating air pollution and enhancing energy security. However, several elements suggest that finding a sustainable transition for the transport sector is particularly challenging. Despite the wide set of policy measures implemented globally to reduce transportation carbon intensity and reliance on oil, CO_2 emissions from the transport sector increased by about 2%

a year from 2010 to 2016 [34]. The continued growth in carbon emissions from the transport sector is attributable to the fact that the growth in transport activity resulting from increasing populations, GDP and income levels is proceeding at a faster pace than improvements to the performance of transport technologies. Emissions from the aviation and maritime sectors continue to grow, suggesting that more cooperative international efforts are needed to reverse the trend. At the same time, emissions from all modes of road transport (cars, buses, trucks and two-wheelers) have also kept on rising, attributable in part to the preference of car buyers for bigger and heavier vehicles worldwide [35]. In Europe, this trend sums up to decreasing sales of diesel cars, which have lower CO_2 emissions than gasoline cars, but are worse in emitting pollutants. Overall these developments are outweighing the positive effects of rising sales of hybrid and electric cars and in 2018 led to the average fuel economy improvements of light-duty vehicles slowing down to 1.4% per year, the lowest rate since 2005 [35]. Some of the main challenges hindering the sustainable transition of the transport sector are related to the following facts.

Transport activity is tightly coupled with GDP and to population and income levels, factors that are increasing in many countries worldwide. In particular, by 2050, the global population is expected to have grown by 30% compared to 2015 [1]. In addition, given the increase in the urbanization rate, two-thirds of the global population will be living in cities, the same place where countries' economies will develop the most, especially in emerging economies. Therefore, due to increases in prosperity, urban populations will potentially be responsible for higher consumption levels of goods and services, more transport activity and greater ownership of private vehicles [1]. This highlights the need to dedicate a special focus on the urban dimension when addressing future mitigation measures for reducing transport energy consumption and emissions.

Sustainable transport technologies are already available on the market, but their high investment costs are slowing their widespread acceptance and thus call for policy support [4]. Moreover, the adoption of low-carbon technologies is being hampered by the slow turnover rate of existing vehicle fleets and the lock-in effect derived from the existing infrastructure.

The growing demand for flexible freight transport implies a greater utilization of trucks, especially in emerging economies, where the road infrastructure is rapidly expanding, leading to trucks being regarded as among the fastest growing sources of global oil demand [5].

The increasing penetration of e-commerce and digital technologies such as Mobility as a Service (MaaS), sharing mobility and autonomous vehicles might result in additional overall transport activity, with potentially negative impacts on energy consumption and emissions from transport [36].

The successful low-carbon transition of the transport sector requires major policy and technology developments and relies on the ability of policy-makers to identify the challenges and to implement an all-encompassing set of measures aiming at addressing them.

Recently, IEA analysed the possible future evolution of the global transport sector in two scenarios: the New Policies Scenario (NPS) and the Sustainable Development Scenario (SDS). The NPS investigates how the global energy sector will evolve in the light of officially declared policy measures and regulatory frameworks, including government commitments in the Nationally Determined Contributions under the Paris Agreement, and taking into account the development of known technologies [12].

In particular, under the NPS, total energy-related CO_2 emissions rise by 10% in 2040 compared to 2017 levels. CO_2 emissions from the transport sector grow to 9.6 Gt in 2040, 20% more than today. The increase in energy-related CO_2 emissions under the NPS, together with non-energy-related GHG missions coming from other sectors, would lead to a global temperature rise of 2.7°C by 2100, not in line with the Paris Agreement, which aims at a 1.5-2°C maximum rise [10]. The energy-related CO_2 emissions resulting from the NPS's assumptions are within the levels declared by countries' Nationally Determined Contributions. However, these commitments are far from being sufficient to limit the rise in average global temperature in line with the Paris Agreement.

The SDS describes how the future energy and transport system should evolve to be in line with the Paris Agreement, in parallel with achieving a drastic reduction in air pollution and broader energy access. In particular, under the SDS, transport CO_2 emissions decrease by 30% compared to today by 2040. This is also possible thanks to the deployment of the IEA decarbonisation strategy for the transport sector called: Avoid, Shift, Improve, which is presented in details in the following section. More insights on the energy outlook under the NPS and SDS for the transport sector are available in Paper **I**.

2.2.2 AVOID, SHIFT, IMPROVE STRATEGY

Getting transport on track to meet global environmental goals such as the Paris Agreement [10] requires putting into practice a broad set of measures, summarized in the IEA's slogan Avoid, Shift, Improve. Avoid entails mitigating transport activity by limiting the number of trips and reducing their distances. Shift consists in limiting the reliance on carbon-intense modes of transport by enhancing the use of, e.g., public transportation and non-motorised modes. Improve implies enhancing vehicle efficiency by adopting more efficient power trains, replacing oil-based fuels with low-carbon fuels, increasing vehicles' occupancy and load factors and light weighting. This section describes the main recent developments and trends relative to the three key pillars of transport decarbonisation.

The measures included in the category Avoid are those that aim at reducing energy consumption and emissions from transport primarily through a reduction in activity (measured in passenger-kilometres or tonne-kilometres). Such measures enable people to satisfy their daily needs while avoiding taking a trip or limiting its distance and ensuring that goods are delivered while minimizing their overall distance. For instance, urban design is an important driver of transport activity. Compact cities or neighbourhoods that include both residential dwellings and commercial or business activities enable shorter trips [1]. A wider adoption of intelligent transport systems (ITS) can also reduce total distances travelled by suggesting shorter routes and can mitigate congestion by recommending less busy routes. Teleworking and virtual mobility are increasingly being adopted by companies and have the potential to reduce their employees' transport activity levels, also resulting in less congested roads and less busy public transport during peak hours. A wider deployment of logistical hubs and the concurrent enhancement of logistical services can improve the overall freight supply chain, resulting in lower freight transport activity.

The actions grouped under the category Shift aim at reducing transport externalities by replacing carbon-intense modes of transport with low-carbon ones. Fig. 2.1 illustrates the rationale behind shift measures: rail has the lowest energy intensity in the passenger transport sector and the second lowest (after shipping) in freight transport [37]. Therefore, in the case of passenger, shifting transport activity from private modes of transport or aviation to public transport enables energy consumption to be limited significantly.

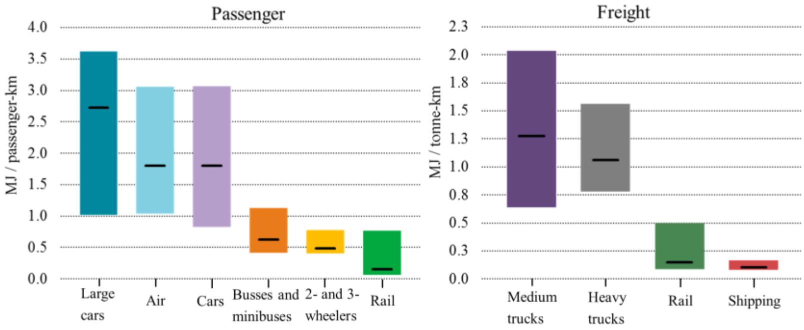


Fig. 2.1*. Comparison of the energy intensities of different transport modes (passenger and freight). The boxes indicate the range of average energy intensity in various countries, while the horizontal black lines represent the world averages. Source:* [37].

So far, shift policy levers have mainly been limited to urban areas, as reflected by the several targets on the modal share of public transport in the NDCs of several countries [38]. However, shift policy measures generally do not target as much freight and intercity passenger transport.

Proper land-use planning that takes into account integrating the transport sector with the overall urban environment can foster the utilization of active modes of transport such as ‘bike and walk’ and increase public transport ridership. Transit-oriented development should be the urban paradigm for fast-growing cities, facilitating access to public transport and shorter trips.

The measures included in the category Improve are those that aim at reducing the energy intensity of transport by deploying low- and zero-emissions vehicles and replacing carbon-intense fuels with low-carbon fuels. The size of the global electric vehicles fleet is increasing rapidly. The stock of electric cars at the end of 2018 reached 5.1 million globally [39], 45% of which was located in China (Fig 2.2). Sales of electric cars were about 2 million in 2018, up 68% compared to 2017 and achieving a 2.7% sales share globally.

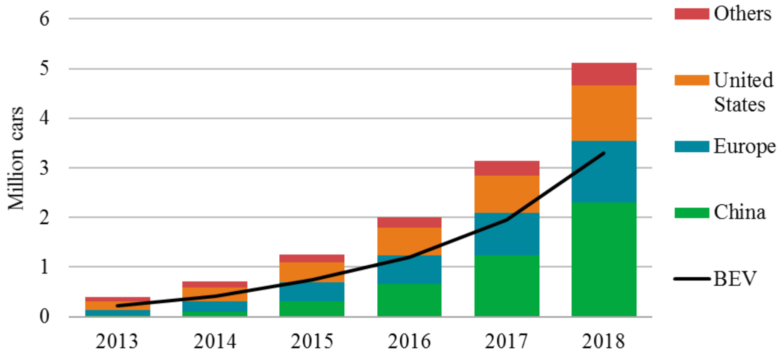


Fig. 2.2. *Passenger electric car stock in main markets (bar graph), 2013-2018. Results include battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), while the black line represents global stock for BEVs. Source:* [39].

While China leads the electric mobility sector in absolute numbers, Norway and Iceland have the highest sales shares, reaching 46% and 11% respectively in 2018. Cities that are experiencing a particular surge of electric vehicles include Shenzhen (China), whose bus fleet has been completely electrified, and Oslo (Norway), where 55% of car sales were electric last year.

Global biofuel production in 2018 grew by 7% with respect to the previous year, reaching about 3.7 EJ (152 billion litres). The IEA expects such production to grow at 3% per year in the next five years [40]. Brazil is the global leader in biofuel production and consumption, reaching record levels of biodiesel and ethanol production in 2018. The consumption of biofuels in the United States and Europe still occurs in the form of blended fuel additives to fossil fuels at low percentages.

While an increasing portfolio of low-carbon technologies is becoming available for short-distance inland transport, the shipping and aviation sectors are still facing a slow uptake of clean technologies (due also to the high price compared to conventional technologies) and are proving to be the most difficult to decarbonize. The low energy density of batteries constitutes the main hurdle to the electrification of aviation, long-distance road transport and shipping. Currently, biofuels, synthetic fuels or hydrogen seem more attractive low-carbon solutions for these sub-sectors, as long as their production chains follow sustainability criteria. The low-carbon transition of the aviation sector is being encouraged through the Carbon Offsetting and Reducing Scheme for International Aviation (CORSIA), the regulatory framework that aims to stabilize GHG emissions from the international air travel by 2020 [41]. For the shipping sector, in 2018 the International Maritime Organization (IMO) approved the target of reducing its GHG emissions by 50% by 2050 with respect to 2008 levels [42]. However, the policy measures needed to reach this target have not yet been identified. The only binding regulatory framework is still the Energy Efficiency Design Index (EEDI), a fuel-efficiency standard mandating a minimum improvement of energy efficiency for new ships [43] and a policy imposing a cap of 0.5% on the sulphur content of maritime fuels [44] (for more details see Paper **I**).

3 LITERATURE REVIEW IN A NORDIC CONTEXT

The Nordic region represents an interesting case. So far a strong commitment for decarbonising the power and heat sector has been pursued, leading to remarkable achievements regarding a wide deployment of renewables. However, when coming to the transport sector, stronger measures are needed. Indeed, despite a transition towards a low-carbon Nordic transport sector has slowly started, transportation represents the largest source of Nordic GHGs emissions, accounting for 40% of total CO_2 emissions and representing a higher share compared to the global average.

This chapter reviews the state-of-the art of studies applying energy system analysis for integrated energy and transport scenarios for the Nordic region, and identifies research gaps and limitations while providing recommendations and possible solutions. This chapter attempts at answering to **RQ2** and is draft based on Paper **II** and partially on Paper **III**, where ulterior details can be found.

In Section 3.1, the criteria adopted for the review are provided. In Section 3.2 a summary of the review results is presented. In particular, the identified studies are commented based on their specific research questions and the methodology applied. Finally, Section 3.3 identifies the research gaps and discusses the motivation to fill them. Moreover, a set of best practice examples is provided based on additional relevant literature, and insights on the implications of adopting such practices are discussed within an energy system modelling rationale.

3.1 REVIEW CRITERIA

The focus of this review is on studies addressing long-term energy scenario analysis for a low-carbon Nordic transport sector, applying energy system modelling as methodological tool. The geographical scope of the review is the Nordic region as a whole; therefore, studies focusing on a single Nordic country are omitted. However, some of them are discussed together with additional relevant literature in Section 3.3. Addressing the Nordic countries as a single region can shed light on possible solution synergies across nations.

The review was carried out during March 2019 through three main steps. First, an automatic literature search of journal articles was performed through online academic databases, namely, Web of Science [45], DTU Findit [46] and Scopus [47]. Then a manual screening was executed to filter out irrelevant studies. Lastly, the assembled literature was integrated with additional relevant reports and book chapters selected manually based on the author's knowledge. Details regarding the database screening and the review methodology are available in Paper **II**.

3.2 REVIEW RESULTS

There are several studies investigating long-term energy scenarios for a low-carbon Nordic transport sector from different perspectives. Usually, the research questions targeted, involve the investigation of the potential role of a specific transport technology in the decarbonisation of the Nordic transport sector. The adoption of specific technologies is analysed in terms of effect on the overall energy system or part of it. Broadly speaking, the most common technologies investigated are electric vehicles (EVs), and the adoption of first- and second-generation (forest-based) biofuels and hydrogen as alternative transport fuels.

The effect of a high penetration of EVs on the energy system is the most investigated topic, which is usually addressed via optimization and linear programming such as in [48,49] for the Nordic region, and in [50,51] for the Norther European area (Scandinavia and Germany). The deployment of forest-based biofuels as a long-term mitigation strategy is investigated by [52] for the Fenno-Scandinavian (Norway, Finland and Sweden) road transport sector. The role of hydrogen in the transition towards a sustainable transport sector is investigated by [53] for the Northern European area together with [54], which includes also biofuels in the analysis. Ref. [55] analyses the technical and economic potential of different hydrogen technologies in the Nordic region under different assumptions.

Only few studies investigate how to achieve a low-carbon Nordic transport sector taking into account the entire energy system in the modelling framework. These studies go beyond the sole interaction between, e.g. the power and transport sectors, but they explicitly account for all the other sectors (from the supply to, e.g. industry and households). Such studies provide a more comprehensive analysis of how to achieve a low-carbon Nordic energy system while providing sector specific insights including dedicated transport analysis. Indeed, this approach potentially allows the identification of synergies between technologies and of resource competition across sectors while fulfilling common environmental targets. For instance, [56] applies a TIMES model of the Scandinavian energy system to investigate pathways towards carbon neutrality by 2050. The transport sector is analysed under a “no import of biofuels” assumption and a low electrification of heavy duty vehicles, resulting in hydrogen as the dominant fuel. Furthermore, [57] analyses how to achieve a 100% renewable share of primary energy supply in the Nordics by 2050 applying TIMES-VTT, a full energy system model of Denmark, Finland, Norway and Sweden. Specifically, the study investigates the role of power-to-gas technologies under different assumptions involving the availability of forest biomass for energy use and the penetration of biofuels and hydrogen in the transport sector.

To summarize, all the mentioned studies analyse long-term low-carbon energy scenarios for the Nordic transport sector with slightly different geographical scope. Most of these studies apply a BU optimization E4 model such as TIMES or Balmorel. They address specific research questions, which are usually centred around a single or limited set of technologies. The integration of the studied technologies is investigated with respect to only a part of the energy system, for instance, the power sector. Only a few studies include the whole energy system [56,57]. Lastly, most of the identified studies focus only on road transportation, while either neglecting the rest of the transport sector or including it partially.

Despite a few years since its publication, the most comprehensive study addressing long-term energy scenarios for a low-carbon Nordic transport sector is the Nordic Energy Technology Perspectives (NETP) 2016 [13], the second of this series. In this series of studies, the modelling framework includes the whole Nordic energy system. Moreover, insights on the possible role of specific transport technologies are provided for the decarbonisation of the entire Nordic transport sector (including inland, navigation and aviation).

NETP 2016 follows the principles of the ETP series of studies by IEA [13], whose aim is to identify sustainable energy technology transition pathways, globally and for specific regions. The ETP-TIMES model represents the backbone of the approach, where the five Nordic countries (Denmark, Finland, Iceland, Norway and Sweden) are described as separate model regions. ETP-TIMES represents the Nordic energy conversion sectors (electricity generation, refineries, etc.) and is soft-linked to three end-use sector models (namely industry, buildings and transport), utilized to derive projections of final energy demands. The transport sector is represented by the Mobility Model (MoMo) developed by IEA [58]. MoMo is a techno-economic spreadsheet and simulation model capable of making detailed projections of transport and vehicle activity, energy demand, direct and well-to-wheel (WTW) GHG and pollutant emissions ([13], p. 224).

NETP 2016 focuses on a central scenario, the Carbon Neutral Scenario (CNS), where Nordic energy-related CO_2 emissions drop by 85% by 2050 compared to 2013 levels. The less ambitious Nordic 4 Degree Scenario (4DS) is also included. It reflects the Nordic contribution to the IEA's global 4DS ([13], p. 35), where the global increase in GHG emissions is limited to 20% relative to 2013 levels ([1], p. 32).

A detailed review of the transport analysis tackled in the NETP 2016 and the rest of the discussed studies is available in Paper **II**.

3.3 IDENTIFIED CHALLENGES AND RECOMMENDATIONS

In light of the literature review, some recommendations are drawn for future long-term energy scenario analysis for a low-carbon Nordic transport sector. Challenges and gaps are identified in the reviewed literature based on recent findings in transport research tackling sustainable mobility. The identified gaps are categorized as: "Transport behaviour", "Breakthrough technologies", "Domestic energy resources" and "Geographical aggregation and system boundaries". Recommendations to overcome the identified gaps are based on forefront studies targeting long-term energy scenario analysis for the transport sector but including other geographical scopes than the reviewed ones. Table 3.1 summarizes the studies tackling the identified gaps in their methodological framework. Each of the examples is commented in terms of effects/repercussions on the scenario analysis within an energy system modelling rationale. In particular recommendations and best practices are mostly provided for BU optimization E4 models, the most common model category applied in the reviewed literature.

The following sub-sections discuss separately the identified gaps by introducing motivation, discussion and recommendations.

Table 3.1. *Examples of studies tackling the identified challenges in their works.*

Challenges	Solution Examples
Transport behaviour	
Modal competition	[20], [59], [60], [61], [62], [63]
Autonomous vehicles and MaaS	-
Breakthrough technologies	
Electrified roads	[64]
Fuel cell and battery electric trucks	[65], [66], [67], [68]
Electric ferries	-
Carbon capture and storage	[69], [70], [71], [72]
Domestic energy resources	
Biofuels - 2nd generation	[21]
Electrofuels	[73]
Geographical aggregation and system boundaries	
Urban dimension	[61]

3.3.1 TRANSPORT BEHAVIOUR

As pointed by [74], the behavioural dimension is crucial when investigating mitigation solutions for transport energy-related CO_2 emissions. However, E4 models are still weak at simulating behavioural changes. There have been some attempts to fill this gap by incorporating behavioural features in integrated energy and transport models [75]. However, these attempts do not appear in most of the reviewed studies. The NETP 2016 represents an exception; behavioural aspects are included in MoMo. However, emerging phenomena deeply dependent on the behavioural dimension, such as autonomous vehicles, car-sharing, car-pooling and in general MaaS are only indirectly considered when estimating car ownership reduction and efficiency increase potentials (due to more efficient driving patterns) ([13], p. 120). The direct inclusion of the behavioural dimension in E4 models could enable the investigation of behavioural change policies. This is particularly relevant when new mobility trends are integrated in the analysis as it gives the possibility to assess effective policies promoting a sustainable adoption of such measures. Moreover, non-motorized modes are not directly modelled in MoMo, though they are considered when estimating passenger transport activity in urban areas. The explicit modelling of such modes could allow analyses of interactions between them and public transport or, potentially, MaaS in terms of complementarity or synergies as underlined by [76].

As presented in [75], the inclusion of behaviour into integrated energy and transport models recognize two main approaches. The first involves linking the E4 model with an external transport model, which incorporates the behavioural dimension and that determines, for example, the modal shares, e.g. through constant elasticity of substitution (CES) [77], multinomial logit (MNL) functions [78,79], or through elasticities [80]. Transport models have been simulating modal choice for a long time to analyse short and mid-term developments of the transport system of a country, region or city as, for example, in the case of Ireland [81], California [82] and Thailand [83]. Thanks to their highly disaggregated description of the population and their ability to base decisions on many attributes, transport models are valid tools for assessing households' modal choice.

The second approach consists of broadening the E4 classical framework to integrate some transport specific variables/dimensions to emulate transport behaviour in order to estimate endogenously, for example, modal choice or shift. Thanks to the inclusion of simulation methods in the model structure, top-down (TD) [84] and hybrid (H) [85,86] E4 models are able to simulate modal choice through CES and MNL functions, which have been used for this purpose for more than four decades, thus being very reliable. Instead, BU optimization energy system models (the most common category applied in the reviewed literature) lag behind TD and H models regarding their ability to represent modal choice or shift. Traditional approaches to represent modal choice, e.g. CES and MNL functions, do not fit directly in the optimization framework, (normally based on linear programming). However, few methods have been developed to include behaviour in BU optimization E4 models. For instance, [20,59,60] emulate modal shift by integrating the concept of travel time budget and transport infrastructure, [61,62] introduce endogenous modal choice through modelling modal level of service and consumers' decisions, while [63] adopts substitution elasticities to enable modal shift. This latter methodology is part of the novelty produced by this PhD thesis and it is presented in details in Chapter 5. These approaches include different levels of transport behaviour representation in the modelling framework and thus offer different capabilities and require different data sources. Therefore, such methodological adoption is dependent on the specific research question addressed by practitioners.

NETP 2016 can be roughly categorized in the first approach recognised by [75]. Instead, the remaining studies reviewed adopt BU E4 models with an aggregated/partial representation of the transport sector, where behaviour is not endogenously modelled. Enhancing the capability of E4 models to capture behaviour dynamics represents a desirable improvement when tackling transport energy scenarios. For instance, the mentioned methodologies are capable of enabling endogenous modal shift, one of the pivotal measures identified by the IEA [8,9] for a low-carbon transport sector. In addition, emerging phenomena largely affected by behaviour such MaaS (including car-sharing and car-pooling) and autonomous vehicles could be investigated in a more direct way. Indeed, autonomous vehicles could reduce congestion and car ownership and increase mileage (more efficient use of the fleet), especially if coming along with car sharing and pooling, and provide electricity storage in the case of electric vehicles [87]. Nevertheless, if wrong policies are in place, they could instead increase congestion and transport activity (Section 2.2). However, no studies including explicitly these emerging mobility phenomena in energy system models were found, providing an opportunity for further research.

3.3.2 BREAKTHROUGH TECHNOLOGIES

Lately, innovation in transport technologies has gained strong momentum. Therefore, the inclusion of up-to-date breakthrough technologies in the modelling framework is challenged by the continuous innovation pace. However, some emerging technologies particularly interesting for the Nordic case can be identified.

In the NETP 2016, electrified roads and fuel cell (FC) trucks are identified to have the potential of suppling part of the long distance road freight transportation ([13], p. 21). Despite this, electrified roads are excluded from the analysis, while FC trucks are only partially included due to their technical and economic uncertainty. There is an undoubted benefit in outlining a scenario demonstrating that policy targets can be achieved with well-known and available technologies. However, the NETP 2016 could have employed less probable and innovation rich scenarios (also known as "wild cards" or "black swans") to test the response of the system under circumstances "beyond the expectations", as recognized by [88]. The inclusion of electrified roads in the analysis represents a desirable improvement, especially considering that electric and hybrid vehicles are highly deployed within the NETP 2016 scenarios (Paper **II**, Section 3.2) and in many of the reviewed studies. In addition, pilot projects assessing their technical and economic feasibility are already ongoing in Sweden, Germany and USA [5], which can provide preliminary figures. Moreover, a high deployment of hydrogen long haul trucks and hybrid or battery electric (BE) regional trucks could be interesting, especially when considering limited bioenergy resources [56].

Electric ferries represent another interesting technology, currently under development by different companies in the Nordics [89]. In MoMo, shipping includes only freight transportation while maritime passenger transport is not directly included. However, maritime passenger transportation causes roughly a quarter of total shipping emissions in the Nordic waters, namely 6.5 Mtonnes of annual CO_2 emissions [90]. Moreover, "green" coastal shipping is compliant with one of the main barrier to expand coastal shipping activity, which is coastal air quality, therefore, low-carbon vessels represent also an attractive alternative for the growing freight road transportation.

Summarizing, electrified roads, FC and BE trucks and electric ferries represent potential breakthrough technologies for the Nordic region. The inclusion of these technologies in the scenario analysis would enable the assessment of the impacts of hydrogen and electricity demands on the whole energy system. This is particularly important in the Nordics, where the electricity system is already accommodating large amounts of intermittent sources (e.g. wind power), and thus hydrogen production and electricity smart charging could represent additional flexibility sources [53]. Considering the available literature, some studies analyse the effect of electrified roads on the power system through the representation of their electricity demand as done by [51]. To the author's knowledge, the only study including explicitly such technology in a BU E4 model is represented by [64], which evaluates the economic viability of electrified roads in the decarbonisation of the Danish transport sector. An explicit inclusion of hydrogen long haul trucks and battery powered trucks appear in more studies, addressing, for instance, energy scenarios for South Africa [65], Japan [67,68] and even globally [66]. Lastly, no studies including electric ferries in energy system models are available.

Another interesting technology is carbon capture and storage (CCS). In the Nordics, the adoption of CCS is particularly interesting for emissions reduction in the heavy industries [91]. This is reflected in the NETP 2016 CNS, where a wide adoption of CCS accounts cumulatively for almost 30% of total direct industrial CO_2 emissions reduction over the period 2020–2050 ([13], p. 24). Even though CCS cannot be directly applied in the transport sector, its inclusion in the analysis is still interesting when looking at dedicated transport scenarios. In particular, when the full energy system is described in the modelling platform, and a common environmental goal is set up (such as a carbon budget), CCS technologies can provide flexibility in reducing emissions across sectors. For instance, CCS can free biomass feedstocks for biofuels production in sectors where alternative solutions are limited (such as aviation or heavy industries [92]). Moreover, the development of bio-energy with carbon capture storage (BECCS) technologies has recently grown in interest in the Nordics [93], given their tradition in heat and power generation from biomass and the large potential for feedstocks. BECCS technologies could be employed to obtain negative emission "credits" from the combustion of biomass to be spent in other sectors where emissions are harder to reduce. Lastly, CCS technologies are particularly relevant for the Nordic region because of its large CO_2 storage potential [94]. However, the inclusion of CCS technologies in BU optimization E4 models is nowadays nearly a common practice, e.g. [69-72].

3.3.3 DOMESTIC ENERGY RESOURCES

The use of bioenergy as a mitigation measure represents a controversial topic. In the CNS, the Nordic region becomes a net importer of bioenergy, by increasing net biofuel imports four times to meet the growing demand in transport, which in 2050 represents two thirds of total final energy use (0.48 EJ, Paper **II**, Figure 1). This vision is framed within a carbon constrained global context where, most likely, the demand for bioenergy will increase as well. Decarbonizing the Nordic transport sector relying heavily on biofuels imports could be questionable in terms of sustainability; therefore, [56] includes a scenario where biofuels imports to the Scandinavian region are excluded. Following a similar approach when investigating sustainable pathways for the Nordic region is recommended. Challenging the studied scenarios with net-zero bioenergy imports spurs the investigation of an efficient strategy to allocate domestic biomass feedstocks across sectors. Furthermore, there are several promising emerging biofuel conversion pathways (mostly forest-based or second-generation) [95], whose inclusion in energy system models is growing in interest, as shown by [96]. Concerning the independence from alternative fuels imports, electrofuels represent also a promising option for transportation [97]: providing an additional alternative to fossil fuels also in those cases where solutions are limited (such as aviation) [98].

Given the high potential for domestic biofuel production in the Nordics [99], an up-to-date bio-refinery technology portfolio is recommended to be included in the analysis, as done, for example, by [21] in the MARKAL_Sweden model. The same applies for electrofuels, whose role in decarbonising the Nordic transport sector could be investigated quantitatively by including them in the modelling framework, as done by [73] in the JRC-EU-TIMES model. Lastly, hydrogen, besides being used in the electrofuels production, represents a potential alternative transport fuel itself, whose production technologies should also be included, as often done in E4 models, e.g. by [100]. Implementing an exhaustive representation of alternative fuel production chains in energy system models provides two main benefits. First, it sheds lights on the optimal use of domestic energy resources. Secondly, in the case of hydrogen and electrofuels, it provides insights on energy storage capabilities in a system with high penetration of variable renewables, such as the Nordic.

3.3.4 GEOGRAPHICAL AGGREGATION AND SYSTEM BOUNDARIES

The urban area is often mentioned as an increasingly important dimension when analysing the future of mobility due to the increasing urbanization rate (Section 2.2). However, cities, due to the high population density and short distance travel patterns, have the potential to promote the adoption of specific sustainable mobility solutions such as non-motorised modes, public transport and electric vehicles [13] (Paper **I** and **II**). In particular, Nordic capitals are already global leaders in sustainable transportation (e.g. Copenhagen's bike lanes, Oslo's electromobility, Stockholm's public transport) ([13], p. 108) and thus represent cutting-edge case studies. Moreover, urban planning influences considerably transport behaviour, not just driving patterns but also modal choice [101]. Therefore, urban planning represents itself a long-term policy instrument for energy demand reduction, which should be integrated in the scenario discussion [102]. However, the urban dimension is neglected in the modelling framework for most of the reviewed studies. The NETP 2016 represents an exception, where, for the first time within the ETPs, the urban dimension is analysed with special focus and dedicated tools.

Capturing the urban dimension in integrated energy and transport analyses allows to depict the great potentials of cities in deploying effective mitigation measures. This is especially true for long-term scenario analysis, where the slow changes in the urban structure, which usually involve a long time span, become feasible and open for policy discussion. Several energy system models have been developed for specific cities to support integrated energy and transport analysis such as for Malmø [103], Oslo [24] and the Helsinki region ([13], p. 232). Other studies differentiate between urban and non-urban transportation in national BU E4 models. One example is given by [61], which provides a modelling design characterizing transportation across the urban, suburban and rural areas for Denmark.

In addition, when investigating energy pathways for a low-carbon transportation sector in the Nordic countries, addressing these countries as parts of a unique system can shed lights on additional solutions by encompassing more options and synergies. However, it is crucial to keep a detailed description of the individual countries, given their differences in, e.g. the geography, resources availability and travel habits, which result in heterogeneous transport challenges [104]. This is done for example by [56,57]. Instead, in the NETP 2016, Nordic countries in MoMo are aggregated into two regions: "EU Nordic" (Denmark, Finland and Sweden) and "Non EU Nordic" (Iceland and Norway). The split of results at a country level is achieved with approximate methods mainly based on population [105]. Depicting single country description enables the identification of specific national strategies and policies while pursuing a common Nordic goal. A similar suggestion can be drafted for the energy system depicted by the modelling platform. Indeed, including all sectors of the energy system in the analysis, as done by [13,56,57], can shed lights on resource competition and technological synergies across sectors when fulfilling common environmental targets, such as the exploitation of waste heat from bio refineries as heating source.

Moreover, in ETP-TIMES, each Nordic country is modelled as a single region since the ETP 2013 study. In the NETP 2016, the electricity trade across the different power regions is assessed with the support of Balmorel. An interesting improvement could be to model the power regions inside the main modelling framework, as done by [56], allowing interregional trade of electricity and, potentially, of other commodities (e.g. biomass or hydrogen), resulting in a fully integrated tool. This is especially relevant considering all the above suggestions, involving the inclusion of different energy carriers and their production chains. Moreover, with the exception of the NETP 2016, in most of the reviewed studies, international shipping and aviation are not part of the analysis. However, mitigation strategies in these sub-sectors are strongly needed (Section 2.2); therefore, their inclusion is necessary for a more exhaustive outlook.

Lastly, the accounting of well-to-tank (WTT) emissions, as in the case of NETP 2016, is recommended, as long as they are consistently integrated in the analysis framework. For instance, for domestic production, they could be directly calculated by including fuel production chains in the modelling platform as suggested above. In addition, a good practice is also the inclusion of additional GHGs emissions (besides CO_2). In fact, the use of alternative fuels in the transport sector could bring some surprises if such emissions are left unchecked. For instance, incomplete methane combustion in internal combustion engines (ICEs) or leakages from pipelines could represent a possible issue, given its larger global warming potential compared to carbon dioxide [6].

Except for the urban dimension, examples are not provided to tackle the rest of the suggestions since they represent only modelling choices and do not involve any novelty.

4 TIMES-NORDIC

This chapter describes TIMES-Nordic, the model developed within the SHIFT project, to which the PhD student contributed substantially as one of the main research activity of his studies. In Section 4.1, the main model architecture is briefly introduced, while in Section 4.2, a special focus is posed on the transport sector description. This chapter is mainly draft based on Paper **III** and Paper **IV**.

4.1 GENERAL OVERVIEW

TIMES-Nordic belongs to the TIMES models family (see Section 2.1). TIMES-Nordic is a multi-country model under continuous development; at the actual stage, it includes only the Scandinavian countries: Denmark, Norway and Sweden. However, as suggested by the name, the inclusion of Finland and Iceland is planned among the next research activities. TIMES-Nordic is intended to be an open-source model aimed at the investigation of long-term energy scenario analyses for a sustainable future of the whole Nordic energy system. Public accessibility to energy models and their inputs is important not only because enabling science transparency and reproducibility, but also for peer-validation and errors corrections as argued by [106].

The modelling architecture of TIMES-Nordic has been thought in order to fill part of the gaps identified in the Nordic studies reviewed in Chapter 3. As suggested in Section 3.3.4, each country is modelled individually and is geographically aggregated into different regions, as shown in Fig. 4.1. For Denmark and Sweden model regions correspond to the Nord Pool power regions, while for Norway power regions are aggregated into two macro-regions: NO1 (South) and NO2 (North). Regions are interconnected through the representation of transmission lines, allowing electricity trade. The full energy system of each country is described in TIMES-Nordic. The modelling structure of each national energy system replicates the architecture of TIMES-DK, the TIMES model representing the Danish energy system [107]. The whole national energy system is divided into five sectors: supply, power and heat, industry, residential and transport. Some of the sector descriptions vary across countries due to major differences in the respective national economies. For instance, for Norway and Sweden, the “Iron and Steel”, “Aluminium”, “Pulp and Paper” and “Mining” industrial sectors are added respect to the original structure of

TIMES-DK. TIMES-Nordic is calibrated for the base year (BY) 2010 and has techno-economic projections until 2050. The whole time horizon is flexibly sub-divided into periods of various length, ranging between one and ten years (according to the user's needs). Moreover, every year is sub-divided into 32 consequential time slices representing seasonal (four seasons), weekly (working/non-working days) and daily variations.

More information on TIMES-Nordic, including most recent modelling updates and instructions to download the model are provided in Chapter 7.

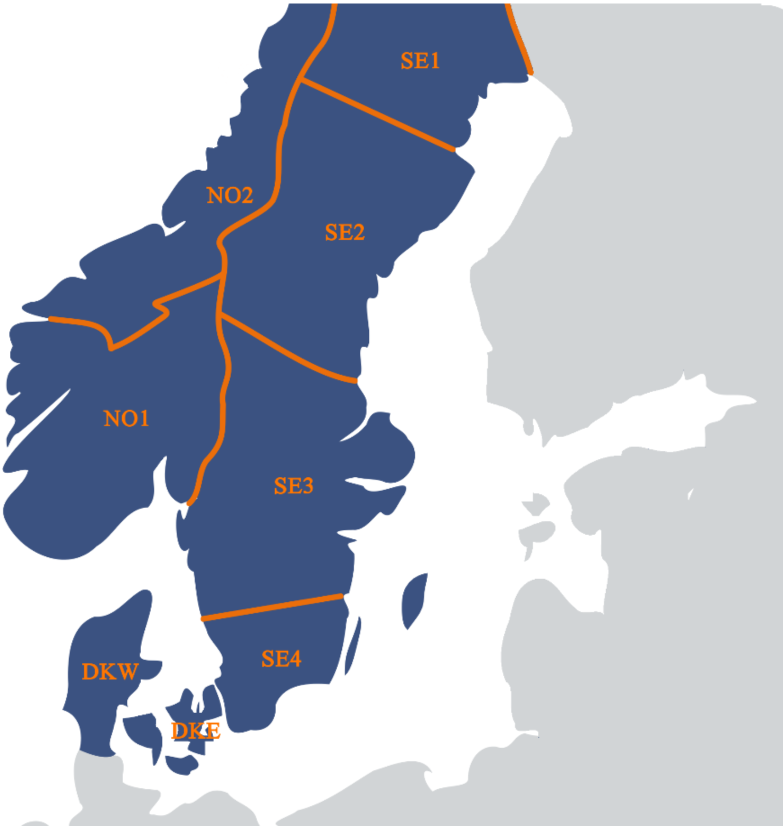


Fig. 4.1. *Model regions in TIMES-Nordic. Modified from* [108].

4.2 TRANSPORT SECTOR

In TIMES-Nordic, each national transport sector comprises passenger and freight transportation in their entirety, both characterised in terms of mobility demands and end-use transport technologies. Fuels can either be traded in the international market or produced by refineries, bio-refineries or other production technologies (such as electrolysers in the case of hydrogen). The domestic production of transport fuels accounts for the use of primary inputs, such as electricity and biomass. In particular, national domestic potentials for biomass are assumed to be shareable across regions, allowing the model to consume them where optimal. Fuels transportation from production sites to end-users is modelled only through their delivery costs. A simplified representation of refuelling stations is also implemented. The only energy carrier whose transmission and distribution is explicitly modelled is electricity. Lastly, the combustion of biofuels is assumed carbon-neutral and only CO_2 emissions are accounted in TIMES-Nordic.

As recommended in Section 3.3.3, a set of alternative fuels production chains have been modelled in TIMES-Nordic. Concerning domestic first-generation biofuels, ethanol can be produced via fermentation of corn and sugar beet roots, while biodiesel through transesterification and hydrotreatment of vegetable oil (rapeseed). Second-generation biofuels production includes biomass-to-liquid biodiesel and biokerosene from straw, and methanol from wood chips and wood waste material, while ethanol can be produced via fermentation of straw. Hydrogen can be produced through alkaline electrolysers, coal or biomass gasification (such as woody material and straw), natural gas, biomass or ethanol steam reforming and Kvaerner process. Synthetic natural gas can be produced via methanation of biogas, whose production processes are also modelled into TIMES-Nordic (e.g. digestion of straw, grass and manure). Lastly, only one electrofuel production process is modelled, which produces methanol by sequestrating CO_2 from the air.

Each sector is divided into inland, aviation and navigation. Inland passenger transportation comprises ten modes: car, bus, coach, rail (metro, train, light rail), two-wheelers (motorcycle and moped) and non-motorized modes (bike and walk), while the inland freight sector comprises three modes: van, truck and rail. Instead, aviation and navigation comprise only one mode each, namely aircraft and ship.

The respective mobility service demands are defined exogenously for each mode for the whole time horizon in the form of passenger-kilometres (pkm) and tonne-kilometres (tkm). In addition, modal demands are split further into distance range classes. For the inland passenger, these are extra short (*XS*, <5 km), short (*S*, 5–25 km), medium (*M*, 25–50 km) and long (*L*, >50 km). For passenger navigation and aviation modal demands are split into National and International depending on whether the demand is part of a domestic or international voyage.

Freight modal demand are split into national short (*NS*, <50 km), national long (*NL*, >50 km) and international (*I*). However, for rail and ship, national demand segments are not split further into short and long, while freight aviation comprises only the international demand. The transport sector structure is presented in Fig. 4.2.

Moreover, for inland freight modes (truck and rail), the *I* class includes only that portion of international transport demand that occurs within the national borders. The same applies for inland passenger modes, only the international transport demand occurring on national territories is included in the respective demand categories. On the contrary, the international freight and passenger ship demands are estimated based on the international bunker consumption as reported by national energy statistics (such as [109]), thus they includes also transport performance outside the national borders. The same applies for aviation. The inclusion of international navigation and aviation in the modelling framework is among the suggestions outlined in Section 3.3.4.

Each transport mode is characterised by an exogenously defined travel pattern (TP), a constraint defining the percentages travelled in the different distance classes. Technologies in a given mode supply the mobility demands in the different distance classes accordingly to the defined share. In the case of passenger transport, TPs reflect population travel habits, while for freight they represent typical modal adoption with respect to distance. TPs are country-specific quantities, which can also vary across regions. The TPs adopted for each region are presented in Paper **IV** (Appendix A). For instance, for passenger transport, TPs are obtained based on National Travel surveys: [110] for Denmark, [111] for Norway and [112] for Sweden.

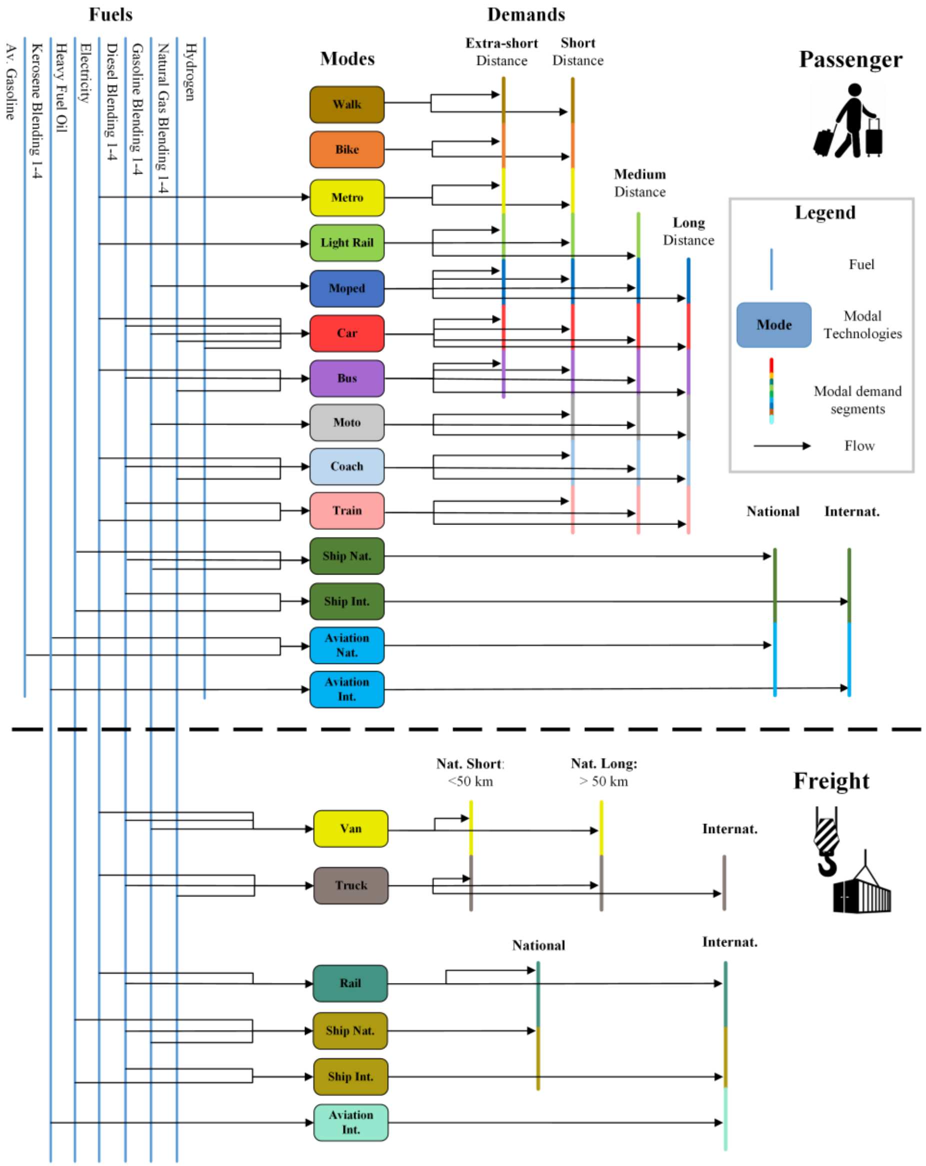


Fig. 4.2. *Transport sector structure in TIMES-Nordic. The length of each coloured segment, representing a portion of each distance range class covered by a specific mode, is not representative of the magnitude of the specific modal demand. Modified from* [20] *and expanded.*

For each mode, a set of existing and future technologies is defined. These technologies differ in terms of fuel use, efficiencies and costs, though technical features such as mileage, average occupancy rates and load capacities are mainly assumed to be equal within the same mode. Modal technical features are estimated in the BY based on aggregated national transport statistics, and are adjusted through model calibration. Therefore, for a specific country, modal technical features are representative of the existing national vehicle fleet composing that mode. For instance, in the BY, one technology is defined respectively for national and international freight ships, whose technical features are representative of a varied fleet mix including, for example, cargo, bulk carriers, roll-on/roll-off and lift-on/lift-off ships. Modal technical features assumed in TIMES-Nordic are presented in Appendix B.

As suggested in Section 3.3.2, a set of breakthrough end-use technologies (available for future investments) have been included in TIMES-Nordic for each mode (though not all the suggestions have been addressed yet). Cars include the following vehicle types: diesel, gasoline and gas blending ICE, battery electric, hydrogen fuel cells, gasoline blending plug-in hybrid and flex fuel ethanol ICE. Moto and moped include gasoline blending and flex fuel ethanol ICE 2-wheelers. Busses and coaches include diesel and gas blending ICE, diesel blending hybrid and battery electric vehicles. Light rail and metro include only electric power trains, while passenger and freight trains include both diesel blending ICE and electric vehicles. Trucks options cover: diesel and gas blending ICE and battery electric vehicles, while vans include diesel and gasoline blending ICE and battery electric vehicles. Both passenger and freight ships include diesel blending ICE with the possibility to switch to heavy fuel oil. Lastly, both passenger and freight aircrafts include kerosene blending ICE, while smaller passenger aircraft only aviation gasoline ICE.

All the blending vehicles assume a maximum blending share level increasing over the time horizon: 25% until 2020, 50% until 2035 and 100% for the remaining period. The main source used to characterise end-use technology is [113]. Besides, a set of CCS and BECCS technologies have been also included for the industry and the power and heat sectors (main sources: [114,115]). The calibration of the transport sector, as for the rest of the energy system, relies mainly on the national energy balances, which provide final fuel consumption for the different sub-sectors (rail, road, aviation and navigation). The main sources used are: [109], [116] for Denmark, [117] for Norway and [118] for Sweden. The final energy consumption obtained with TIMES-Nordic for the BY after calibration is presented in Fig. 4.3.

The existing technology fleet, reproducing the energy balance, is characterised based on national transport statistics such as [119] for Denmark, [117,120] for Norway and [118,121] for Sweden and transport technology catalogues such as [113]. The modal mobility demands in the BY are mainly based on the national transport statistics mentioned above, and they are projected up to 2050 based on trends assumed in the CNS (NETP 2016, obtained from the MoMo model - data provided by [122]). When the modal demands were not available per distance categories (most frequent case), the respective modal TPs were used to split them.

Lastly, projections of market fuel prices are also assumed from the CNS (NETP 2016, obtained from the Balmorel model). Projections for electricity prices with neighbouring countries are calculated with the Balmorel model version developed within the Flex4RES research project (funded by NER), whose main scenario assumptions are also aligned with the CNS.

With the presented transport sector structure (Fig. 4.2), the model satisfies the defined modal demands by deploying the technology mix with the lowest levelised costs while fulfilling the ulterior constraints implemented. Competition among transport technologies occurs only within modes, not across them. Therefore, the present modelling structure does not allow the direct inclusion of transport modal shift. The next chapter presents a novel methodology developed within this research project to include modal shift in TIMES models. The methodology represents an attempt to fill the gap identified in Section 3.3.1 related to the representation of behaviour in BU optimization E4 models.

4.3 SCIENTIFIC CONTRIBUTION

Concluding, the scientific contribution of TIMES-Nordic to the Scandinavian energy modelling community is embodied by its modelling architecture, which fills some of the gaps identified in the reviewed literature in Chapter 3. Above all the filled gaps, TIMES-Nordic depicts the full Scandinavian energy system and its entire transport sector explicitly in a single modelling platform. This allows to analyse future possible evolutions of the Scandinavian transport sector considering its interactions and potential synergies/conflicts with the other sectors. This is a crucial feature since transportation is expected to be progressively more interconnected with the rest of the energy system in the future, as witnessed by the strong electrification often analysed in the reviewed literature.

Even though most of the proposed recommendations do not represent per se novel contributions from a strict modelling point of view, filling such gaps paves the way for additional Scandinavian scenario analyses compared to the existing ones. This is even more relevant considering that TIMES-Nordic will soon be an open-source model, facilitating and supporting fellow researchers and modellers to enrich the Scandinavian analysis whilst not being inhibited by the shortcomings identified within the existing literature.

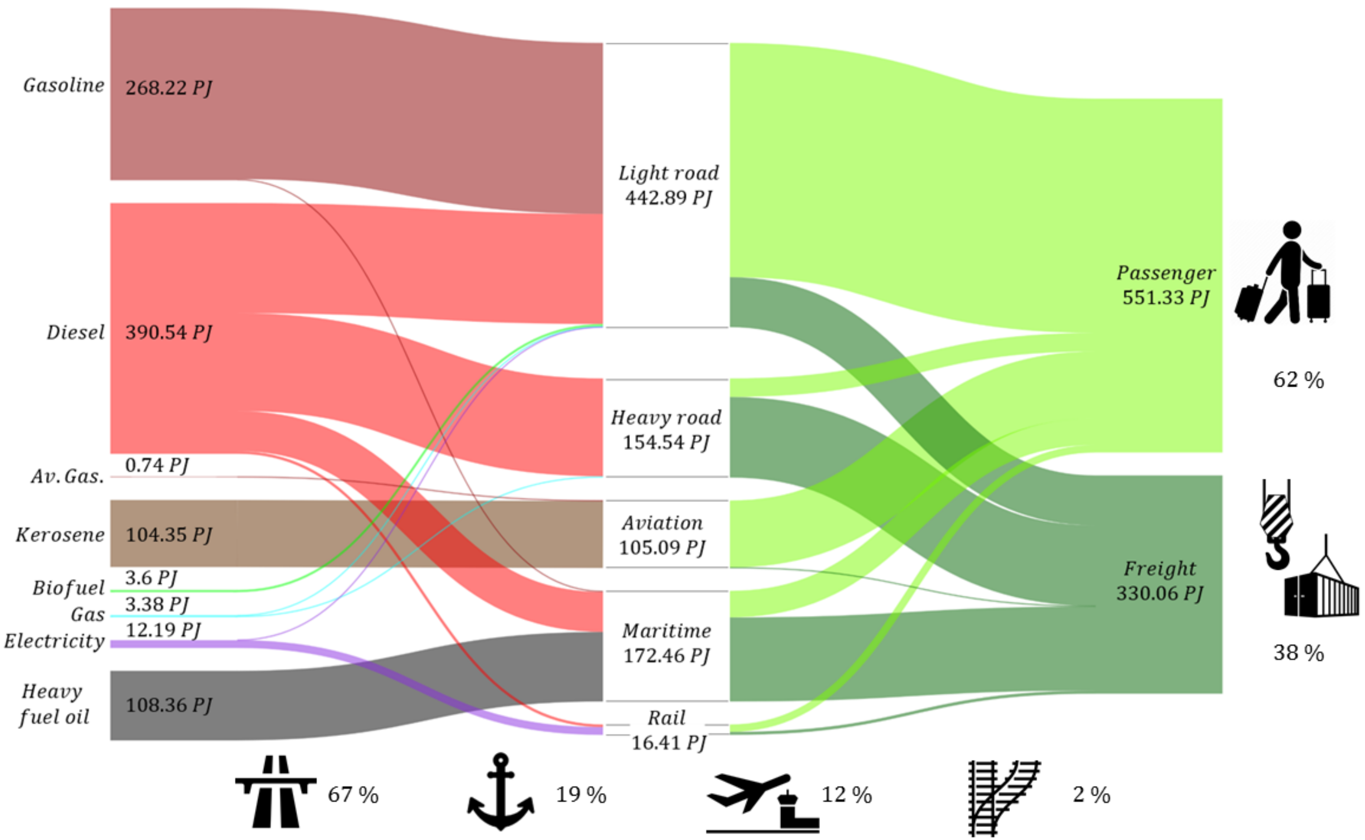


Fig. 4.3. *Final energy consumption and energy flows in the Scandinavian transport sector obtained with TIMES-Nordic for the BY (2010). Including international aviation and navigation.*

5 ELASTIC TRANSPORT MODAL SHIFT

As anticipated in Chapter 3 and 4, a novel methodology was developed within this PhD project to enhance the representation of transport modal competition in BU optimization E4 models. The alternative methodologies presented in Section 3.3.1, enhancing transport description in BU optimization E4 models, focus mainly on passenger, while, to the author's knowledge, the same modelling efforts have not yet been directed to enrich the description of freight transport. The developed method adopts substitution elasticities to characterise transport demand substitution across different modes (for both passenger and freight), enabling the investigation of modal shift: one of the pivotal mitigation measures proposed by the IEA to promote a sustainable transition for the transport sector (Section 2.2). In the case of passenger transport, the methodology attempts at emulating transport behaviour, one of the recommendation outlined in Chapter 3. Indeed, behavioural dynamics are crucial when investigating mitigation strategies for transportation but are only poorly described in this type of models, as witnessed by the recent international research efforts attempting to fill this gap (Section 3.3.1). In the case of freight, where behaviour plays only a limited role, the methodology still enables the characterization of modal competition based on observed market arrangements resulting from variations in modal transport costs. The methodology developed moves a step forward concerning the representation of the transport sector in BU optimization E4 models. Enhancing transport realism represents a relevant scientific contribution since it paves the way for broader and more solid analyses aiming at the decarbonization of this sector.

The aim of this chapter is first, to provide a background on how the demand elastic response is introduced in TIMES models, and second to present the methodology developed to model transport modal shift (answers to **RQ3**).

In Section 5.1, the general theory behind the introduction of demand elasticity response within the TIMES paradigm is introduced. Section 5.2 describes the linearization of the elastic demand functions, while 5.3 provides additional insights on how the elastic response mechanism occurs. Section 5.4 derives the equations adopted to model transport modal shift and Section 5.5 comments upon the developed methodology from a modelling perspective. Please note that this chapter is draft based on ref. [123], [22], [124] and Paper **III**.

5.1 DEMAND FUNCTIONS

Energy system modellers can adopt elasticities to investigate demand variations in response to price changes driven by alternative scenario assumptions (e.g. fuel prices, availability of resources), or in response to specific set of policy measures (e.g. emission taxes, emission cap, etc.). The adoption of elastic demand functions in TIMES models requires the definition of a reference case, where the model calculates the reference shadow prices for the relevant demand commodities. In a second moment, the mitigation policies under assessment are introduced into the model, which alter the shadow prices of the demand commodities. The model determines a new solution, where the elastic demands re-arrange their levels because of changes in their shadow prices. The magnitude of the change is regulated by the elasticity value.

In the TIMES paradigm, each energy service demand $DM_i(t)$ is assumed to have a constant own-price elasticity $E_i(t)$ of the following form:

$$\frac{DM_i(t)}{DM_i^0(t)} = \left(\frac{p_i(t)}{p_i^0(t)}\right)^{E_i(t)} \quad \rightarrow \quad p_i(t) = p_i^0(t) \cdot \left(\frac{DM_i(t)}{DM_i^0(t)}\right)^{\frac{1}{E_i(t)}} \tag{5.1}$$

In Eq. (5.1), $\{DM_i^0(t); p_i^0(t)\}$ represents a pair of demand and price values for the reference case over the time horizon, while $E_i(t)$ is the (negative) own-price elasticity of such demand.

TIMES maximizes the net present value of total surplus of consumers and producers, by means of minimizing the total system costs (represented by the opposite number). The total surplus can be obtained by integrating the difference between the demand price functions and the supply cost functions between zero and the demand level. The integral of the supply cost functions are obtained by taking the vector product $c^T \cdot X$ in net present value, while the demand price functions (second expression in Eq. (5.1)) can be easily integrated (for calculations details see Appendix A). The objective function in the linear program (LP) can be written as follows:

$$Min\ \ c^T \cdot X - \sum_i \sum_t PVF(t) \cdot \frac{p_i^0(t)}{DM_i^0(t)^{\frac{1}{E_i(t)}} \cdot (1 + \frac{1}{E_i(t)})} \cdot DM_i(t)^{1+\frac{1}{E_i(t)}} \tag{5.2}$$

$$s.t.\ \ \sum_k VAR\_ACT_{k,i}(t) \geq DM_i(t) \quad i = 1, \dots, I; t = 1, \dots, T \tag{5.3}$$

$$B \cdot X \geq b \tag{5.4}$$

In Eq. (5.2), PVF is the net present value factor, while X is the vector of all TIMES variables and c^T is the transposed vector of variable related costs. Eq. (5.3) represents the set of demand satisfaction constraints, where VAR_ACT$_{k,i}(t)$ is the activity level of the k-*th* end-use technology producing the energy service demand i. Lastly, Eq. (5.4) is the set of all the other constraints defined. However, the minimization problem (Eq. (5.2)) so obtained is not linear, because of the presence of the terms $DM_i(t)^{1+\frac{1}{E_i(t)}}$.

5.2 LINEARIZATION OF DEMAND FUNCTIONS

The linearization of the elastic response of demand functions can be formulated for demand i in each time period t by defining: a) the percentage range $\Delta_i^{up,lo}(t)$ within which the demand can adjust its level in response to changes in shadow price for the up and low direction with respect to the reference case, and b) the number of steps $m_i(t)$ and $n_i(t)$ used to linearize the elastic response respectively in the low and up direction. It is worth noticing that the definition of the above quantities identifies the step width $\beta_i^{up,lo}(t)$ of the elastic response in the up and low direction. From now on, it is assumed that the number of steps are invariant respect to the time horizon.

For each demand $DM_i(t)$, a set of m and n step variables can be defined for the low and up direction respectively and denoted as: $sm_{j,i}(t)$ and $sn_{j,i}(t)$. Each of the step variables is bounded between zero and the step width $\beta_i^{up,lo}(t)$. Obviously, the number of steps should be high enough to obtain the desired accuracy of the approximation. The demand function $DM_i(t)$ can thus be rewritten as follows:

$$DM_i(t) = DM_i^0(t) - \sum_{j=1}^{m} sm_{j,i}(t) + \sum_{j=1}^{n} sn_{j,i}(t) \tag{5.5}$$

Concerning the non-linear terms $DM_i(t)^{1+\frac{1}{E_i(t)}}$ appearing in Eq. (5.2), they can be approximated around the point $DM_i^0(t)$ as follows:

$$\begin{aligned} DM_i(t)^{1+\frac{1}{E_i(t)}} \cong DM_i^0(t)^{1+\frac{1}{E_i(t)}} + \left(1 + \frac{1}{E_i(t)}\right) \cdot DM_i(t)^{\frac{1}{E_i(t)}}\Big|_{DM_i^0(t)} \\ \cdot \left(DM_i(t) - DM_i^0(t)\right) \end{aligned} \tag{5.6}$$

However, thanks to the step-wise approximation, we can rewrite the second term of the right side of Eq. (5.6) using the step variables and substitute it in Eq. (5.2), obtaining the following form of the LP (for calculation details see Appendix A):

$$\begin{aligned} Min \;\; c^T \cdot X - \sum_i \sum_t PVF(t) \cdot \left(\frac{p_i^0(t) \cdot DM_i^0(t)}{\left(1 + \frac{1}{E_i(t)}\right)} \right. \\ \left. - \sum_{j=1}^{m} p_{j,i}^{-}(t) \cdot sm_{j,i}(t) + \sum_{j=1}^{n} p_{j,i}^{+}(t) \cdot sn_{j,i}(t) \right) \end{aligned} \tag{5.7}$$

$$s.t. \;\; \sum_k VAR\_ACT_{k,i}(t) \geq DM_i(t) \quad i = 1, \dots, I; t = 1, \dots, T \tag{5.8}$$

$$B \cdot X \geq b \tag{5.9}$$

Where $DM_i(t)$ in Eq. (5.8) are now variables and $p_{j,i}^{\pm}(t)$ are explicitly shown here after:

(5.10)

$$p_{j,i}^{\pm}(t) = \begin{cases} p_{j,i}^{+}(t) = p_i^0(t) \cdot \left(\dfrac{DM_i^0(t) + \left(j - \frac{1}{2}\right) \cdot \beta_i^{up}(t)}{DM_i^0(t)} \right)^{\frac{1}{E_i(t)}} \\ p_{j,i}^{-}(t) = p_i^0(t) \cdot \left(\dfrac{DM_i^0(t) - \left(j - \frac{1}{2}\right) \cdot \beta_i^{lo}(t)}{DM_i^0(t)} \right)^{\frac{1}{E_i(t)}} \end{cases} \tag{5.11}$$

5.3 ELASTIC DEMAND RESPONSE

Following Eq. (5.1), when a mitigation policy (or any other change in the scenario assumptions) is introduced in the system, a decrease or increase in demand occurs when the price of such demand changes compared to the reference price. If the price increases the demand decreases and vice versa, the demand variation is regulated by the elasticity value.

As it can be noted from Eq. (5.7), in the objective function, to each step variable is associated a cost represented by Eq. (5.10-11) respectively for the up and low direction. In particular, increase step variables ($+$) have opposite signs compared to the supply cost function terms, while the decrease step variables ($-$) are concordant with them. Their levels are identified by the model while maximizing the total surplus of consumers and producers in the system. The elastic variation of a specific demand segment takes place only if leading to a decrease in the objective function compared to the inelastic case. This happens when the difference between the cost or yield associated to the step variables and the variation in the supply cost function term ($c^T \cdot X$) due to the change in the demand level, is negative. In particular, considering a one unit change of the *i-th* demand (compared to the reference case), and one linearization step, the increase occurs when the system cost of supplying the additional unit is lower than $p_{1,i}^{+}(t)$; while the decrease occurs when the avoided system cost of supplying one unit less is higher than $p_{1,i}^{-}(t)$.

If we call $c_i'^{\pm}(t)$ the variation of the supply cost function term (in absolute value) due to a one unit increase/decrease of the *i-th* demand in the elastic case and we assume only one linearization step, we can write the following conditions for the elastic response to occur in a specific *t*:

$$\begin{array}{llll} & \textit{Ideal case} & \textit{Linearized case} & \\ \textit{Increase:} & p_i(t) < p_i^0(t) & c_i'^{+}(t) - p_{1,i}^{+}(t) < 0 \rightarrow c_i'^{+}(t) < p_{1,i}^{+}(t) & (5.12) \\ \textit{Decrease:} & p_i(t) > p_i^0(t) & -c_i'^{-}(t) + p_{1,i}^{-}(t) < 0 \rightarrow c_i'^{-}(t) > p_{1,i}^{-}(t) & (5.13) \end{array}$$

In the ideal case, a change in the level of the *i-th* demand would occur as soon as its shadow price $p_i(t)$ deviates from the reference value $p_i^0(t)$. However, in the linearized case, the demand response takes place only when the variation of the supply cost function term is smaller/larger than the threshold values $p_{1,i}^{\pm}(t)$ (Eq. (5.12-13)). Please note that the so obtained conditions are representative for a simplified case, which may ignore exceptions and complexities that are not essential for a basic understanding of the mechanism.

In Fig. 5.1, the elastic response of the *i-th* demand commodity is represented in a simplified diagram for a specific t, and a single step variation of width $\beta_i^{lo,up}$:

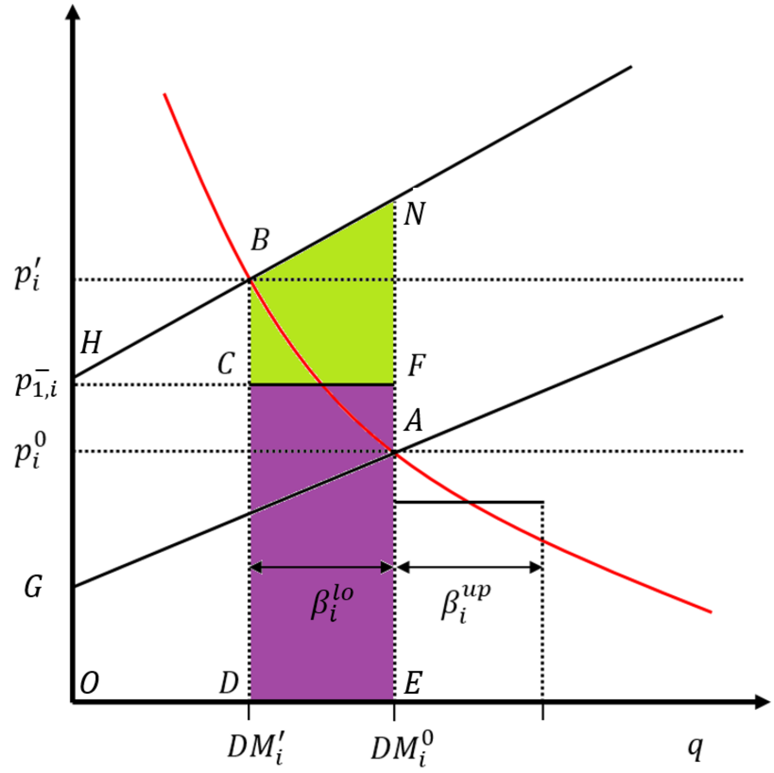


***Fig. 5.1**. Simplified representation of the elastic demand response of* $DM_i(t)$ *for a single step decrease of width* β_i^{lo} *and a specific t. Inspired from* [22,124].

The supply-demand equilibrium in the reference case is represented by point *A*: the intersection between the demand price function and the supply cost function (here simplified by a line), which occurs at reference demand level DM_i^0 and price p_i^0. The total supply cost is, therefore, given by the area of the trapeze *AEOG*. If the mitigation policy (or any other change in the scenario assumptions) under study results in shifting the supply curve upwards, and the demand is assumed not elastic, the new equilibrium is established at point *N* (inelastic-case). In this case, the supply cost is represented by *NEOH*. It is worth noticing that, since TIMES maximize the total surplus of consumers and producers by means of minimizing the total system cost, the difference in total cost between the inelastic case and the reference case represents the loss in total surplus (or Δ surplus), in this case, embodied by the area *NAGH*.

For the elastic case, assuming that the single step variable for the decrease direction is fully exploited, the demand level decreases by β_i^{lo}. The new equilibrium is obtained at point *B*, corresponding to demand level DM_i' and price p_i'. The total cost is now composed by *BDOH* + *FEDC* (purple area). In particular, the area *FEDC* is the elasticity cost (representing the consumer utility loss or Δ utility) embodied by the term $p_{1,i}^{-} \cdot sm_{1,i}$ in the linear program (in this specific case, $sm_{1,i} = \beta_i^{lo}$). In the elastic case, the surplus loss compared to the reference case is represented by the area *BCFAGH*. Compared to the inelastic case, the objective function value is reduced by *NFCB* (green area).

Coming back to Eq. (5.13), where the demand level decreases by one unit, the condition $c_i'^{-}(t) > p_{1,i}^{-}(t)$ is nothing else than stating that in order to trigger a reduction in the demand level, the area subtended by the supply cost function between $DM_i^0 - 1$ and DM_i^0 (avoided cost) minus the elasticity cost ($p_{1,i}^{-} \cdot 1$) should lead to a positive number (total cost in the inelastic case minus total cost in the elastic case), which is represented by the green area.

Moreover, $p_{j,i}^{\pm}(t)$ are monotone functions of $E_i(t)$:

$$p_{j,i}^{\pm}(t) = p_i^0(t) \cdot a_{j,i}(t)^{\frac{1}{E_i(t)}} \tag{5.14}$$

$$where \quad \begin{cases} a_{j,i}(t) > 1 & for \quad p_{j,i}^{+}(t) \\ a_{j,i}(t) < 1 & for \quad p_{j,i}^{-}(t) \end{cases} \quad \forall\, j, i, t \tag{5.15}$$

As shown in Eq. (5.14-15), for every *j*, *i* and *t* and for $E_i(t) \in (-\infty; 0)$, $p_{j,i}^{+}(t)$ is a monotone decreasing function of $E_i(t)$ limited above by $p_i^0(t)$ and below by 0, while $p_{j,i}^{-}(t)$ is a monotone increasing function of $E_i(t)$ limited below by $p_i^0(t)$:

$$p_{j,i}^{+}(t) = \begin{cases} p_i^0(t) & for \quad E_i(t) \to \ -\infty \\ \ 0 & for \quad E_i(t) \to \ 0^- \end{cases} \quad \forall\, j, i, t \tag{5.16}$$

$$p_{j,i}^{-}(t) = \begin{cases} p_i^0(t) & for \quad E_i(t) \to \ -\infty \\ +\infty & for \quad E_i(t) \to \ 0^- \end{cases} \quad \forall\, j, i, t \tag{5.17}$$

In Fig. 5.2, $p_{j,i}^{\pm}(t)$ are represented qualitatively for an arbitrary j and for the subsequent step (j+*1*) as a function of $E_i(t)$:

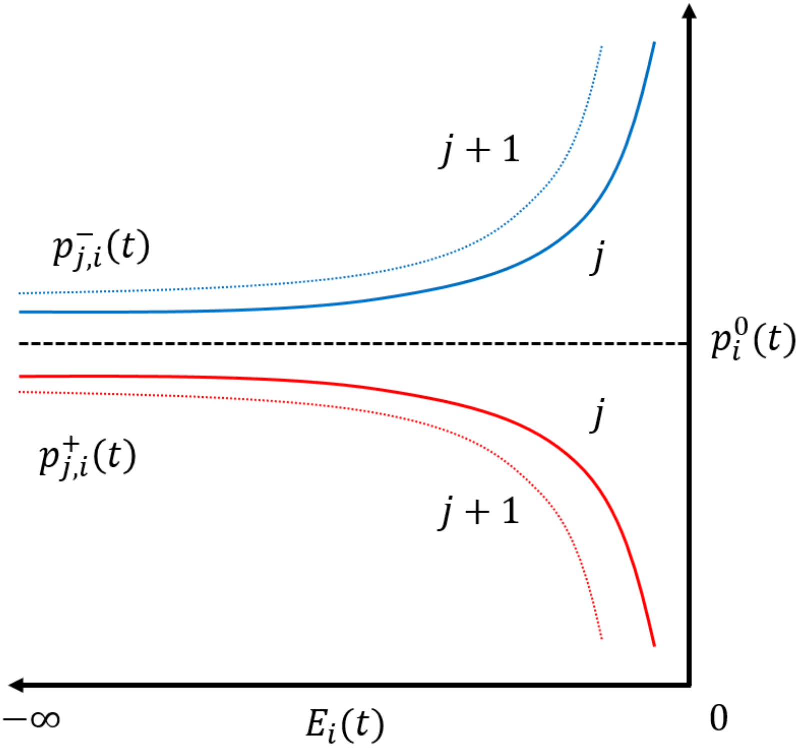


Fig. 5.2*. Qualitative representation of* $p_{j,i}^{\pm}(t)$ *for an arbitrary* j *(continuous lines), and for j+1 (dotted lines) as a function of* $E_i(t)$.

As it can be noted from Fig. 5.2, as $E_i(t)$ tends to $-\infty$, $p_{j,i}^{\pm}(t)$ tends to $p_i^0(t)$. This is equivalent to say that for higher elasticities (in absolute value) the model is more sensitive to change in shadow prices and vice versa. In fact, the difference between the variation of the supply cost function term and $p_{j,i}^{\pm}(t)$ times the variations in the demand level (leading to a negative contribution in the objective function and thus triggering a demand response) is larger for higher elasticity values. In other words, given an upward shift of the supply cost function, higher elasticities entail for lower elasticity cost in the decrease case. Therefore, for higher elasticities, the elastic response tends to occur for smaller deviations of the supply cost curve compared to the reference case. Lastly, given a specific $E_i(t)$, because of the progressive increase/decrease of $p^{\pm}_{j,i}(t)$ with respect to j, the optimization ensures that the $sm_{j,i}(t)$ and $sn_{j,i}(t)$ variables are increased consecutively and in the correct order. For ulterior details regarding $p^{\pm}_{j,i}(t)$ please see Appendix A.

Summarizing, the elastic demand response is introduced in the TIMES paradigm by defining additional variables (piece-wise functions). The demand response occurs only when leading to a decrease in the objective function value compared to the inelastic case. The space of the feasible solutions of the linear program includes a set of additional solutions where the demands have different levels (non-null step variables) compared to the inelastic case. However, the case where the demands do not vary their levels is still part of the space of the feasible solutions. In fact, if the mitigation policy does not stimulate any change in the shadow price of the elastic demands, the inelastic solution will still be the optimal one. Therefore, the elastic linear program is a less constrained problem compared to the inelastic case.

5.4 SUBSTITUTION MECHANISM

Until recently, only the linearized own-price elasticity formulation was available in the TIMES code. Lately, the demand functions formulation has been generalised in order to include elastic substitution across demands involving constant elasticity of substitution (CES) aggregates by [123]. Ref. [123] provides different set-ups to model substitution elasticities in TIMES. In this thesis, a specific set-up has been adopted to model transport modal shift. Therefore, only the set-up applied is discussed.

Given a set of energy-service demands $DM_i(t)$, and assuming that the different demands can be substitutes of each other, an aggregate k grouping them can be defined. Each demand composing the so obtained aggregate can be denoted by $DM_{k,i}(t)$, and can be linearized as presented in the previous sections:

$$DM_{k,i}(t) = DM^0_{k,i}(t) - \sum_{j=1}^{m} sm_{k,j,i}(t) + \sum_{j=1}^{n} sn_{k,j,i}(t) \tag{5.18}$$

In order to model a substitution mechanism within the aggregate k, a common elasticity of substitution $\sigma_k(t)$ can be defined in the aggregate. Each of the component demand would then be characterised by the same own-price elasticity value. Based on this, the coefficients of the demand price function terms for the step variables (Eq. (5.10-11)) can be written as follows:

$$p_{k,j,i}^{\pm}(t) = p_{k,i}^{0}(t) \cdot \left(\frac{DM_{k,i}^{0}(t) \pm \left(j - \frac{1}{2}\right) \cdot \beta_{k,i}^{up,lo}(t)}{DM_{k,i}^{0}(t)} \right)^{\frac{1}{\sigma_k(t)}} \tag{5.19}$$

As it can be noted from Eq. (5.19), now the elasticity value $\sigma_k(t)$ is not anymore dependent by the index i, but it is rather a representative value for the aggregate.

In order to have the aggregate volume preserved after the elastic response, an ulterior condition is required:

$$\begin{aligned} DM_k'(t) &= \sum_{i=1}^{N_k} \delta_{i,k}(t) \cdot DM_{k,i}(t) \\ &= \sum_{i=1}^{N_k} \delta_{i,k}(t) \cdot DM_{k,i}^{0}(t) - \sum_{j=1}^{m_k} zm_{j,k}(t) + \sum_{j=1}^{n_k} zn_{j,k}(t) \\ &= DM_k^{0}(t) - \sum_{j=1}^{m_k} zm_{j,k}(t) + \sum_{j=1}^{n_k} zn_{j,k}(t) \,; \quad \forall t \in T \end{aligned} \tag{5.20}$$

Where $DM_k^0(t)$ and $DM_k'(t)$ are the weighted sums of the N_k component demands composing the aggregate k before and after substitution respectively and $\delta_{i,k}(t)$ are the substitution rates between component i and aggregate k (which in the simplest case may all be assumed equal to 1). The terms $zm_{k,j}(t)$ and $zn_{k,j}(t)$ are the step variables used to linearize the elastic response of the aggregate demand relative to its own-price variation.

In this study, the own-price elasticity for the aggregate k is assumed null, and the substitution rates $\delta_{i,k}(t)$ are all assumed unitary. In particular, the latter assumption is necessary to guarantee that the demand substitution retains the physical volume, e.g. forcing 1 pkm of rail transport to be substituted for each pkm of car transport. In this specific case, Eq. (5.20) reduces to Eq. (5.21) (volume-preserving condition):

$$DM'_k(t) = \sum_{i=1}^{N_k} DM_{k,i}(t) = \sum_{i=1}^{N_k} DM^0_{k,i}(t) = DM^0_k(t); \quad \forall t \in T \tag{5.21}$$

The new levels of component demands are obtained in the elastic case by means of maximizing the total surplus of consumers and producers, while satisfying the new constraint (Eq. (5.21)). Considering only two component demands in the aggregate *k* and assuming only one linearization step, the substitution occurs, for a specific *t*, in the elastic case only if satisfying the following inequality (based on Eq. (5.12-13)):

$$\begin{aligned} c_1'^{+}(t) - p_{1,1}^{+}(t) \cdot sn_{1,1}(t) - c_1'^{-}(t) + p_{1,1}^{-}(t) \cdot sm_{1,1}(t) + c_2'^{+}(t) \\ - p_{1,2}^{+}(t) \cdot sn_{1,2}(t) - c_2'^{-}(t) + p_{1,2}^{-}(t) \\ \cdot sm_{1,2}(t) < 0 \end{aligned} \tag{5.22}$$

However, since a demand cannot increase and decrease its level at the same time, and since the volume-preserving condition imposes that if one demand varies its level, then the other has to vary by the same quantity but in the opposite direction, we can rewrite Eq. (5.22), for the specific case where demand 1 increases its level by one unit and demand 2 decreases it by one unit:

$$(c_1'^{+}(t) - p_{1,1}^{+}(t)) + (-c_2'^{-}(t) + p_{1,2}^{-}(t)) < 0 \tag{5.23}$$

Eq. (5.23) can be written in a more compact way as follows (Eq. (5.24)) and three specific cases, which satisfy the inequality can be identified (Eq. (5.25)):

$$\alpha + \gamma < 0 \tag{5.24}$$

$$\begin{cases} A: & \alpha, \gamma < 0 & \\ B: & \alpha > 0, \gamma < 0, & |\gamma| > |\alpha| \\ C: & \alpha < 0, \gamma > 0, & |\alpha| > |\gamma| \end{cases} \tag{5.25}$$

In case *A*, the mitigation policy (or any other change in the scenario assumptions) leads to an upward shift of the supply cost function related to demand 1 and to a downward shift for demand 2. The shifts are large enough to trigger the elastic response for both demands, which both contribute to reduce the objective function value of the elastic case (compared to the inelastic case). In the other two cases, α and γ are discordant. In particular, in case B, γ is negative, which means that the supply cost function of demand 2 has shifted upwards enough to make the reduction of demand 2 gainful in terms of reducing the objective function value. However, α is positive, which means that the supply cost function of demand 1 has not shifted downwards enough to make the increase of demand 1 gainful with respect to reducing the objective function value. In fact, the supply cost function of demand 1 could also have shifted upwards (a more likely situation for a mitigation policy, e.g. a carbon tax). However, because of the volume-preserving constraint (Eq. (5.21)), demand 1 has to increase its level to accommodate the variation of demand 2 even though α is positive. Therefore, in case B, the demand substitution occurs only if the negative contribution of γ to the objective function is large enough to compensate for the extra cost represented by α. Case C is equivalent to case B but the roles of demand 1 and 2 in the substitution mechanism are inverted.

Summarising, demand segments whose shadow prices have changed enough to stimulate an elastic price demand response can vary their levels only if other demand components defined in the aggregate vary by the same quantity but in the opposite direction. This can lead, to situations where, for instance, demand segments increase their levels only to accommodate variations of other demand segments, even though their shadow prices have remained unchanged or have even increased compared to the reference case, representing an additional cost for the system and thus shrinking the reduction of total system cost compared to the inelastic case.

The condition expressed by Eq. (5.23) is representative for a simplified case, which may ignore exceptions and complexities that are not essential for a basic understanding of the mechanism. Additional insights and observations related to the application of the developed methodology are presented in the next Section.

5.5 ADDITIONAL INSIGHTS

Each of the demand component $DM_{k,i}(t)$ composing an aggregate k can vary their levels only in relation to their exogenous values $DM_{k,i}^{0}(t)$, by a theoretical maximum change of ±100% (identified by $\Delta_{k,i}^{up,lo}(t)$). Two first observations can be articulated. First, the applicability of the developed methodology is limited to such cases where modal shift can occur within a 100% change relative to the original modal travel demands. Second, ceteris paribus, larger demand segments can vary more than smaller demand segments.

Given a specific aggregate k, a theoretical maximum modal shift can be calculated as: how much the highest potential contributors to the shift among the demand segments in the aggregate ($\Delta_{k,i}^{up,lo}(t) \cdot DM_{k,i}^{0}(t)$) can accommodate or be accommodated among the rest of the component demands, given their shift potentials and according to the variation directions. However, such theoretical maximum is hard to achieve due to few dynamics.

As mentioned in Section 5.3, higher elasticities values entail for higher demand variations, and thus higher transport modal shift. This is shown clearly in Paper **III** (Section 4.2), where a sensitivity analysis on how the substitution elasticity values affect transport modal shift is presented. However, the sensitivity analysis reveals also a saturation of modal shift before reaching its theoretical maximum. Usually, when a specific environmental policy or target is set up, the supply cost functions of transport modal demands shift upwards for most of transport modes compared to the reference case. The volume-preserving condition forces some of the demand segments, to increase their levels only to accommodate variations of other demand segments even though their shadow prices have increased compared to the reference case, representing an additional cost for the system and thus reducing the attractiveness of shifting demands across modes. This represents a first dynamic contributing to the saturation observed in modal shift. A second mechanism is the interaction between modal travel patterns and the substitution mechanism. This will be explained in more details in Chapter 6.

Lastly, the use of substitution elasticities to model transport modal shift has the advantage to be a relative compact and simple method compared to alternative approaches, such as [20,59,60]. Indeed, the data requirements is low and consists mainly of the identification of the substitution elasticities $\sigma_k(t)$, and the modal shift potentials $\Delta_{k,i}^{up,lo}(t)$. Contrary to [20,61], the methodology proposed relies only to a minor extent on national travel surveys, while the external support of national transport simulation models is not required. The low data requirements is also reflected by a simple modelling structure (presented in details in the next chapter), which relies on the use of a standard set-up [123]. Moreover, as pointed out by [124], the LP resulting from the inclusion of elastic demands is augmented by a number of variables but only to a minor extent by new constraints compared to the inelastic case. Therefore, the developed methodology has very minor impact on computational time. These pros represent a preferable approach for a large multi-country model such as TIMES-Nordic.

6 TIMES-NORDIC ANALYSIS

This chapter presents a first application of the developed methodology for a real case study (draft based on Paper **III** and **IV**). The main scientific contribution presented in this chapter is to show the applicability of the methodology by using transport elasticities from the literature. In particular, transport modal shift is introduced in TIMES-Nordic and the elasticity type that best suits the modelling environment is identified (among the available ones), discussed and adopted. Lastly, the results reveal the positive contribution of modal shift in reducing transport emissions in the Scandinavian region within a long-term scenario analysis framework and under an increasing CO_2 tax. Section 6.1 presents the structure of the TIMES-Nordic transport sector with elastic modal shift. Section 6.2 introduces the analysis context: the identification of substitution elasticities from the literature and the scenario assumptions. Section 6.3 presents the main results. Section 6.4 provides a discussion and further perspectives, while Section 6.5 presents a few additional analyses aimed at testing the solidity of the obtained results. This chapter provides answers to **RQ4**.

6.1 TIMES-NORDIC WITH MODAL SHIFT

The TIMES-Nordic transport sector structure with elastic modal shift is presented in Fig. 6.1. The main difference with the original version lies in the demand side structure (as it can be noted comparing Fig. 6.1 with Fig. 4.2). In Fig. 6.1, for every region and for a specific year t, each distance range class k (where $k = XS, S, M, L, NL, I$) represents an aggregate, where all corresponding travel demand segments $DM_{k,i}(t)$ (where i represents the mode, $i = 1,\ldots, N_k$) are grouped together and a common elasticity of substitution σ_k is defined. Modal demand segments, composing an aggregate k, can endogenously adjust their levels in response to changes in their shadow prices compared to a reference case. Moreover, the total volume of each aggregate k is constrained to be conserved after substitution (volume-preserving condition, Chapter 5), assuming that each mode is a perfect substitute of the others.

For passenger, only inland modes participate in modal shift, while for freight, modal shift involves truck, rail and ship. Since freight modal shift from road towards rail and shipping is considered infeasible for short distances, as argued by [125] and [126], vans are excluded from modal shift, while for trucks, only long distance demand segments (*NL* and *I*) are assumed to participate. Lastly, aviation is excluded from the modal shift analysis.

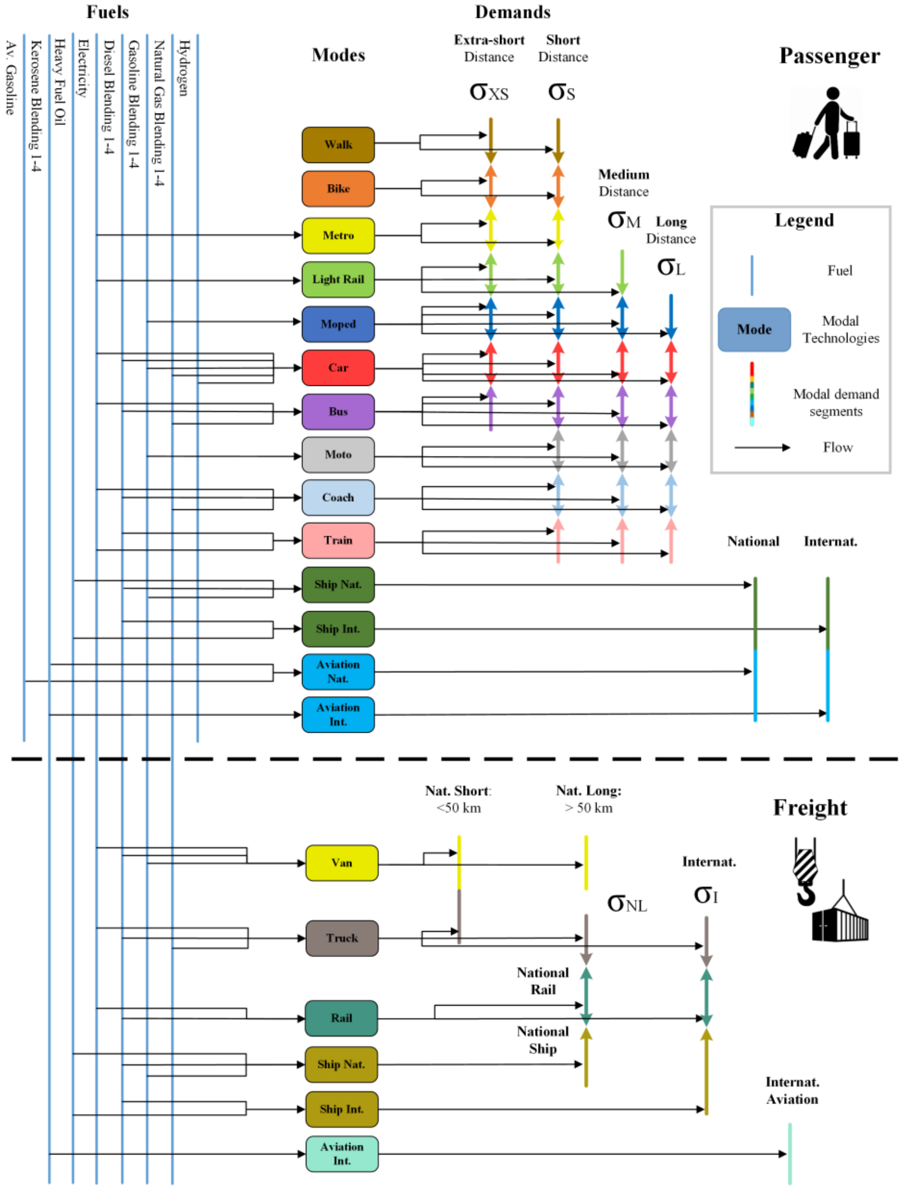


Fig. 6.1. *Transport sector structure in TIMES-Nordic with elastic modal shift. The length of each coloured segment, representing a portion of each distance range class covered by a specific mode, is not representative of the magnitude of the specific modal demand. Modified from Paper* ***IV****.*

6.2 ANALYSIS CONTEXT

6.2.1 SUBSTITUTION ELASTICITIES

A vast literature is available on transport elasticities, including review studies that provide generic recommended values or “most likely” ranges, e.g. [127,128]. Transport elasticities measure the responsiveness of a specific transport quantity, such as modal transport demand, fuel consumption or traffic levels, to changes in other factors, which can range from fuel price to total transport costs, parking fees, road tolls or transit fares for public modes etc. [129,130]. Different methods can be applied to estimate such quantities, such as time series analysis, transport surveys and logit models [131]. Usually elasticities are provided for the short, medium or long terms, generally referring to a response taking place respectively within a year, five years or more [129]. Moreover, where transport modes compete, elasticities can be provided in the form of direct or cross elasticities, depending on whether the responsiveness measured for a certain mode is the result of a change in a transport factor affecting the same mode or another one.

The identification of proper values for σ_k to simulate modal shift represents a challenge (as pointed out in Paper **III**). Indeed, the computational framework of transport elasticities includes a large variety of transport variables, which are not always captured among the transport dimensions and costs represented in energy system models. The following paragraphs attempt at identifying transport elasticity categories suitable for this purpose. This is an essential step required to apply the presented methodology, as important as its development.

Given the modelling structure adopted to mimic modal shift, long-term own-price (or direct) elasticities are identified as the elasticity category most suitable for this purpose. Indeed, TIMES-Nordic covers a forty-year time horizon, which for this specific study case, is broken down into time periods of ten years, where investment decisions are taken with perfect foresight. Thus, long-term elasticities, which represents the effect of price changes over a long period potentially involving change in technology stock, are the preferred category. Moreover, given a specific modal demand, the demand price function coefficient of each step variable involved in the elastic response is computed based on its own modal demand shadow price estimated in the reference case (see Chapter 5). Therefore, even though the new modal demand level is obtained by also taking into account the variations in the other demands composing the aggregate, because of the volume-preserving condition, the main mechanism driving the elastic response represents an own-price elastic response dynamic.

Least but not last, in TIMES models a demand shadow price is calculated as the marginal change of the objective function per unit increase in the demand level [22]. Therefore, the shadow price includes all types of cost related to meeting the additional demand unit, potentially covering variable and fixed costs, fuel costs, investment costs etc. Hence, an elasticity representing variation in transport demand (Mpkm or Mtkm, dependent variable) due to a percentage change in the total transport cost (explanatory variable) represents the preferred quantity to adopt in this modelling framework because of its consistency with the travel costs defined in the model.

In light of the available literature, the elasticities assumed for each mode are shown in Table 6.1 (left side). The identified values are similar to those proposed by [132] for use in energy system models, except for the road transport elasticities, which are slightly higher. The so identified modal elasticities are assumed representative of the distance class k where the highest demand for the selected mode is defined. The characterization of modal elasticity for the other distance categories is achieved in light of literature providing elasticities per trip distance (additional details can be found in Paper **IV**). Table 6.1 (right side) provides also the values for σ_k, which should be representative of the modal demands mix composing the aggregate k. Therefore, they are calculated as the weighted average of the identified modal elasticities using as weights modal demands in 2020. For simplicity, no differentiation across regions is introduced.

***Table 6.1. Left side**: long-term own-price elasticities assumed for each transport mode with original sources. **Right side**: substitution elasticities assumed for each aggregate k. *Original sources indicate the references used to identify the modal elasticities, for assumptions and calculations steps see Paper **IV**. Elasticities are provided as pure numbers because they are dimensionless quantities.*

	Mode	**Elasticity**	**Source***	k *Aggregate*	σ_k *Substitution elasticity*
Passenger	Bike	-0.58	[133]		
	Bus	-1.1	[127,131]	***XS***	-0.82
	Car	-1.28	[133]		
	Coach	-1.5	[127,131]	***S***	-1.05
	Light Rail	-1.2	[131]		
	Metro	-0.7	[131]	***M***	-1.26
	Moped	-1.28	[133]		
	Moto	-1.28	[133]	***L***	-1.59
	Train	-1.2	[129]		
	Walk	-0.71	[133]		
Freight	Rail	-1.2	[128]	***NL***	-1.66
	Ship	-1.53	[134]		
	Truck	-1.1	[128]	***I***	-1.29

6.2.2 SCENARIO DESCRIPTION

Substitution elasticities are applied to investigate the potential role of transport modal shift in decarbonising the Scandinavian transport sector. The analysis is carried out by comparing the results of two versions of TIMES-Nordic, one with elastic modal shift (TIMES-NordicEMS), the other without (TIMES-Nordic). For TIMES-Nordic, the optimal solution consists in identifying the least-cost portfolios of technologies that fulfil the exogenously provided modal demands, while in TIMES-NordicEMS the optimal solution is identified as a co-optimization of modal shares and technology shares. Thus, modal shift provides TIMES-NordicEMS with additional flexibility when complying with environmental targets or policies.

The two model results are compared for the same “Base” scenario that includes an increasing CO_2 tax, in force from 2020 until the end of the time horizon (2050), and affecting all sectors in the model (Table 6.2). The tax levels adopted are based on the marginal abatement costs obtained in the CNS (which are summarised in [13] at p. 230, Table A.4). Specifically, the CO_2 price levels are taken directly from the Balmorel model analyses carried out as a modelling support for the NETP 2016 project, which were kindly made available by scientists involved in such project. These data are provided for each year of the time horizon and so are declared as inputs to TIMES-Nordic, though for simplicity reason, in Table 6.2, CO_2 tax levels are shown only for selected years.

Marginal abatement costs are usually obtained as the dual value of the constraint imposed to limit the level of emissions over the years. Therefore, imposing a carbon tax with the same levels is an equivalent approach to obtain the same decarbonization trend obtained with the constraint. However, [13] provides marginal abatement costs only for the electricity sector, indeed the decarbonization analysis carried out for the end-use sectors is investigated in separated simulation models (such as MoMo for the transport sector). Since the transport sector is considered one of the most complicated sector to decarbonise, the assumed CO_2 tax levels could be insufficient to achieve the same CO_2 emissions reduction obtained under the CNS. However, the aim of this analysis is to investigate a first application of the developed methodology over than replicating the CNS for the Scandinavian transport sector.

Beside the carbon tax, the analysis is performed as a socio-economic optimization, thereby excluding energy taxes and subsidies and other regulatory market mechanisms.

All the end-use demand projections, including mobility demands, and fuel-market price projections are taken from the CNS assumptions, while expansions in electrical transmission lines are exogenously declared based on the CNS results [13].

Table 6.2. *CO_2 tax over the studied time period. Based on* [13].

Year	2020	2025	2030	2035	2040	2045	2050
2015 €/Tonne of CO_2	6	30	77	92	107	123	130

Modal shift is allowed only after 2020 with an increasing potential. A 25% modal shift potential for both the upward and downward directions $\Delta_{k,i}^{up,lo}(t)$ is assumed for each modal demand segment in 2020, rising to 100% in 2050, with linear interpolations for the years in between. The elastic response for each demand is linearized with ten steps (*j*). Concerning the international demand for freight by ships, only the portion of the demand corresponding to trade between Denmark, Norway and Sweden is included in the aggregate *I*. Details on the estimation of such portion of transport demand can be found in Paper **IV**.

As anticipated in Section 5.5, the interaction between the travel pattern constraints and the substitution mechanism can distort the elastic demand response dynamic. Indeed, exogenous modal demand segments $DM_{k,i}^{0}(t)$ defined across distance range classes follow the same proportions as those outlined by the modal travel patterns. Thus, a modal demand segment variation in a specific distance range class k leads to a different proportion among the demand segments compared to the original one. This could result in an impossibility for the marginal modal technology to satisfy the demand variation, unless the variation is counterbalanced by changes (in the same direction) of the other modal demand segments in the other classes *k*, in such a way that their proportions remain constant and equal to the modal travel pattern. For this reason, travel patterns are relaxed by 5% for all modes from 2012 onwards. Moreover, since the *NS* truck demand does not participate in modal shift, its TP share declared is relaxed by 25% from 2020. In this way, if the other truck demands decrease their levels, the relative share for *NS* is allowed to increase, thus avoiding hindering modal shift.

Lastly, σ_k values are kept constant for all regions and for the whole time horizon. The reference shadow prices are computed in the reference case, which is identical to the Base scenario except that it excludes the CO_2 tax.

6.3 RESULTS

6.3.1 MODAL SHIFT FOR DECARBONISING THE SCANDINAVIAN TRANSPORT SECTOR

The modal shares for TIMES-Nordic and TIMES-NordicEMS in 2050 are compared in Fig. 6.2 for the Base scenario. The overall car demand in the inland passenger sub-sector is 4% lower (about 11,300 Mpkm) in TIMES-NordicEMS compared to TIMES-Nordic. Car is substituted by more efficient modes such as train, metro, light rail and non-motorised modes. In the freight sector, modal shift occurs from truck, the least efficient mode, and, to a lesser extent from ship, to rail, whose demand is 35% higher (about 16,290 Mtkm) in TIMES-NordicEMS.

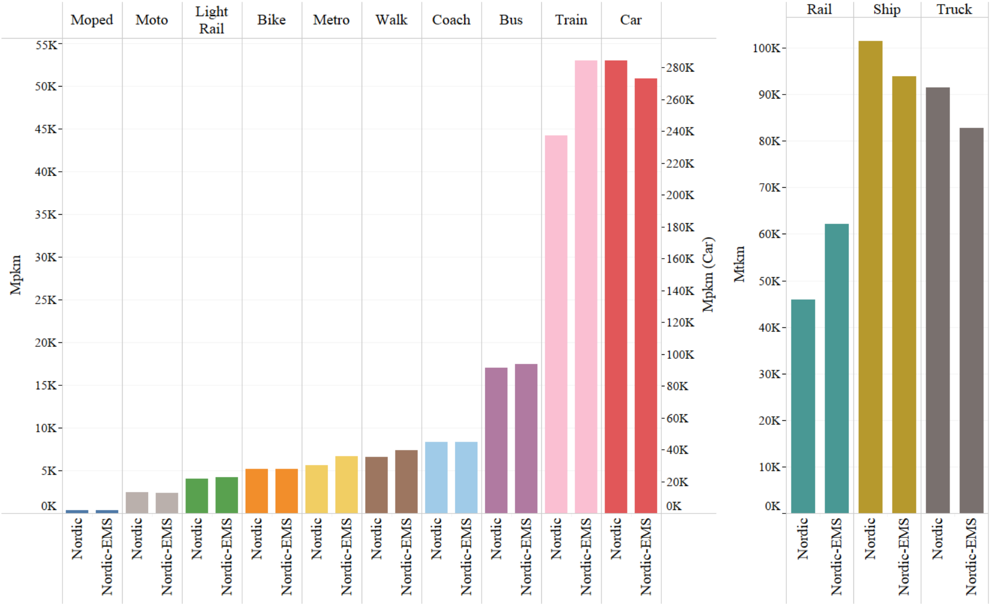


Fig. 6.2. *Comparison of modal shares in 2050 for TIMES-Nordic and TIMES-NordicEMS.* ***Left side****: passenger transport,* ***right side****: freight transport. For the mode ship, only national demand and the portion of international demand due to the Scandinavian trade are shown. Paper* ***IV****.*

Concerning the technology fleet of both models, diesel and gasoline ICE cars are gradually substituted by natural gas ICE cars and to a lesser extent by battery electric (BE) cars, while gasoline-blended ICE cars (using a blend of gasoline and bio-ethanol) play a transitional role, with penetration peaking in 2030–2040. Diesel ICE buses and coaches are substituted by BEVs on the long run, while diesel blending ICEVs (using a blend of diesel and bio-diesel) and natural gas ICEVs are adopted as transition alternatives. Passenger and freight rail modes are fully electrified as the existing stocks (including diesel trains) are phased out. Gasoline ICE mopeds and motorbikes are replaced by gasoline-blended ICE 2-wheelers. Diesel ICE trucks are gradually substituted by natural gas ICEVs, while diesel blending trucks play only a minor role at the beginning of the transition. Diesel and heavy fuel oil freight ships are replaced by flexible fuel ships, which can consume diesel blended with bio-diesel, and heavy fuel oil in variable shares.

Despite the presence of an increasing carbon tax over the time horizon, fossil fuels still play an important role in the end-use sectors in 2050. The fuel consumption of the whole transport sector (excluding aviation) in the Scandinavian region is shown in Fig. 6.3. For both TIMES-Nordic and TIMES-NordicEMS, fuel consumption slightly falls over the time horizon compared to 2010–2020, despite the assumed increase in mobility demand. This is due to improvements in the fuel economy of new vehicles and the slight electrification of the technology fleet. In particular, for passenger, the assumed growth in mobility demand in 2050 compared to 2010 corresponds to 60% for Denmark and Sweden, and 90% for Norway, while for freight it corresponds to 40% for Denmark and Sweden, and 70% for Norway.

From 2030 onwards fuel consumption differs increasingly between the two model versions. TIMES-NordicEMS presents a lower yearly fuel consumption, accounting in 2050 for almost 26 PJ less than TIMES-Nordic (around −4%). This corresponds to a potential emissions reduction of almost 1.6 Mtonnes of CO_2. For the same period, TIMES-NordicEMS is also characterised by about 2.2% lower cumulative CO_2 emissions in the transport sector compared to TIMES-Nordic, corresponding to almost 30 Mtonnes, most of which is attributable to modal shift. The electricity consumption is slightly higher in TIMES-NordicEMS, though when considering CO_2 emissions related to electricity generation, such differences account for only 0.2 Mtonnes of additional cumulative CO_2 emissions compared to TIMES-Nordic due to the low carbon intensity (CI) of electricity generation (Appendix B in Paper **IV**). The lower total system costs in TIMES-NordicEMS compared to TIMES-Nordic (about −0.1%) highlights the cost-effectiveness of modal shift as a measure towards a low-carbon transport sector in Scandinavia.

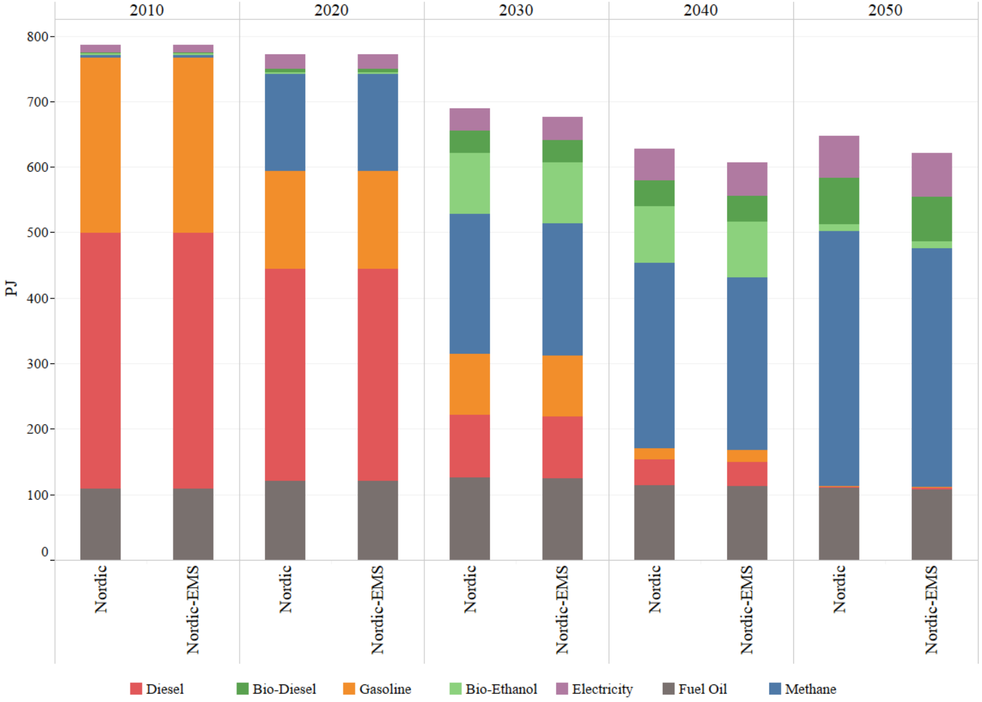


Fig. 6.3. *Fuel consumption in the transport sector for TIMES-Nordic and TIMES-NordicEMS in the Base scenario. Aviation is excluded. Paper* ***IV****.*

6.3.2 PASSENGER MODAL SHIFT

Fig. 6.4 shows the inland passenger modal shift for the three Scandinavian countries. The largest contributor to cumulative modal shift over the studied time horizon and for almost every year is Sweden, followed by Denmark and Norway, which present similar contributions. As described in Chapter 5, ceteris paribus, larger demand segments can vary their levels more than smaller ones. Since Sweden has the greatest inland passenger demands, followed by

Denmark and Norway, the same merit order can be found in the sizes of the modal shift. Modal shift presents a similar trend across the different countries: it increases over the years as a result of the increasing CO_2 tax and shift potentials. The only exception is Denmark, where modal shift in 2050 falls compared to 2040. The reason resides in the reference case, where in 2050, despite the absence of environmental targets and policies, gasoline blending ICE cars penetrate the Danish transport sector with a high share of bioethanol consumption. The bio-ethanol consumed is produced entirely by bio-refineries converting sugar-beet roots. The heat produced by the refining process is also exploited to supply central district heating in Denmark, making bio-ethanol an attractive fuel even where environmental policies are lacking. Bio-ethanol refineries are also installed in Norway and Sweden along the entire time horizon, though bio-ethanol is blended with gasoline at lower percentages. Therefore, in 2050, in the Base scenario, the CO_2 tax causes lower increases in Danish car demands shadow prices with respect to the reference case compared to the other years, resulting in a lower modal shift.

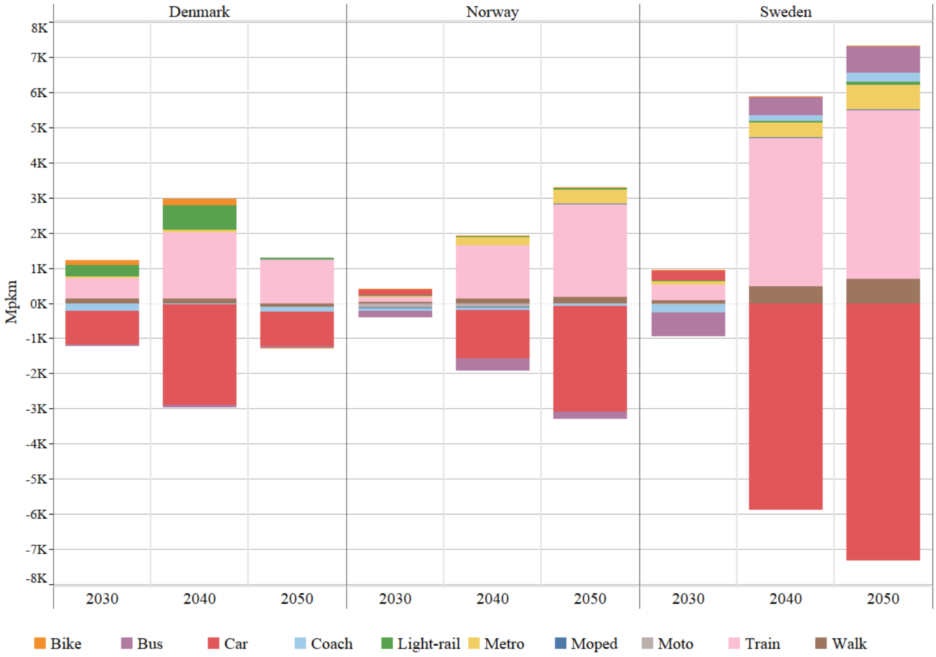


Fig. 6.4. *Modal shift in inland passenger transport in the Scandinavian countries obtained with TIMES-NordicEMS in the Base scenario. Paper* ***IV****.*

Concerning the different aggregates, in *L* and *M* car is mostly substituted by train, given the orientation of its TP towards longer distances. However, for the *M* aggregate, bus and light rail also contribute slightly to reducing car demand in Sweden and Denmark respectively. Within the *S* category, car is generally substituted by metro, light rail, train and non-motorised modes (walk and bike), while in *XS* it is mainly substituted by metro and non-motorised modes, whose TPs include only shorter distance classes. Bus participates marginally to modal shift in all countries, and it does not follow the same trend (Fig. 6.4). In Norway and Denmark, bus demand slightly decreases over the time horizon in all distance categories, while in Sweden it decreases only in 2030, increasing in the remainder of the period. The assumed national modal travel patterns, occupancy factors and efficiencies vary slightly across countries due to different travel habits and geographical characteristics. These differences influence mode competition when enabling modal shift. For instance, in Sweden, bus presents a TP oriented more towards longer distances compared to Denmark and Norway (Table A1, Paper **IV**), while light rail to shorter distances, making bus a more suitable substitute to car, whose demand is generally larger in longer distance classes, especially for Sweden.

Lastly, a sensitivity analysis investigating the response of modal shift to variations in the adopted substitution elasticities (Section 3.2, Paper **IV**) reveals that passenger modal shift still has margin before the saturation (see Section 5.5 for more details on the topic). In particular, in 2050, passenger modal shift saturates at 51,013 Mpkm (corresponding to 39,715 Mpkm additional demand shift with respect to the Base scenario).

6.3.3 FREIGHT MODAL SHIFT

Fig. 6.5 illustrates freight modal shift in each Scandinavian country for the studied time horizon. The largest share of modal shift takes place in Sweden, followed by Norway and Denmark. Also in this case, the largest freight transport demands are present in Sweden, followed by Norway and Denmark, explaining the merit order of the sizes of modal shift.

The mode rail faces the largest demand growth within the studied time horizon, while accommodating ship and truck demands reductions. In the Base scenario, shadow prices for truck and ship demands tend to increase in all countries and in all years compared to the reference case due to the CO_2 tax, while for rail they remain almost constant. The reason is that in the reference case freight trains tend to be completely electrified from 2030 onwards. In addition, electricity generation already relies almost entirely on non-fossil sources by 2020 (Appendix B, Paper **IV**). Thus, the CO_2 tax does not stimulate large changes in rail demand shadow prices: on the contrary, its demand variations are caused mainly by the volume-preserving condition. Therefore, countries with greater rail demands have a higher modal shift potential due to their greater capacity to absorb the other two freight modes demands. Again, Sweden has the highest transport demands for rail freight, which in 2050 accounts for 39,324 Mtkm, followed by Norway with 6004 Mtkm and Denmark with only 627 Mtkm.

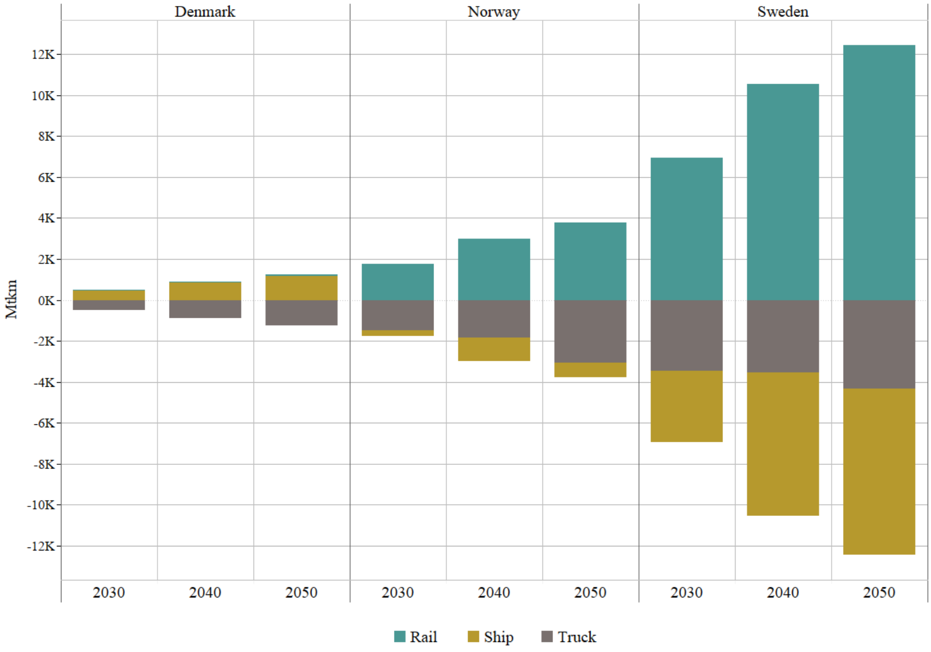


Fig. 6.5. *Modal shift in freight transport in the Scandinavian countries obtained with TIMES-NordicEMS in the Base scenario. Paper* ***IV****.*

Furthermore, in TIMES-Nordic and TIMES-NordicEMS, modal technical features, such as mileage and average load capacities, are estimated based on aggregated national transport statistics (Chapter 4). Thus, for a specific country, they represent an average of a very varied fleet mix. For trucks and ships the calculated technical features are comparable across Scandinavian countries, while rail presents some differences (see Appendix B for details). Rail average load capacities and mileage are almost double in Sweden compared to Norway and triple compared to Denmark. The reason for these differences resides in the composition of the national freight rail sectors, which may include, for example, metal ore trains capable of carrying significant loads, or container trains that carry significantly less. Sweden has the largest mining sector in the Nordics, with fifteen metallic mineral mines. In contrast, Norway accounts for only three mines, while Denmark has no active mines [135]. Moreover, most of the Swedish mining sites are placed in the north, while large industrial sites and harbours are in the south. Therefore, the average technical features estimated for freight trains in Sweden are higher than in the other two countries, increasing the attractiveness of rail compared to other freight modes in the country.

Ship demands mostly fall in all countries over the time horizon, despite the high efficiencies, which for national ships are assumed to be on average 1200 Mtkm/PJ and for international ones almost 6000 Mtkm/PJ. In the model, new freight ships available for investment are limited to consuming heavy fuel oil and a blend of diesel and biodiesel, with increasing shares of maximum blending and improved efficiencies over the years. In the reference case, freight ships consume heavy fuel oil and diesel, while in the Base scenario, some of the diesel is replaced by biodiesel due to the CO_2 tax, resulting in an increase in their demands shadow prices and consequently in a decrease in their demand levels. The only exception is Denmark, where rail freight demands are almost negligible compared to demands for other modes. As a result ship, which represents the second most favourable alternative to trucks, slightly increases its demand levels in every year of the time horizon. The lack of alternative technologies such as gas, ammonia or electric ships is a limitation of this study, whose inclusion could change substantially the potential role of this mode in respect of modal shift in freight transport.

In addition, freight ships are not constrained in terms of TP, since two independent set of technologies supply respectively the national and international demands (Fig. 6.1). Therefore, since TP can hamper the modal shift mechanism (Section 6.2.2), this modelling structure favours ship, while penalising truck and rail in terms of modal shift capability. However, this modelling choice aims to differentiate freight ships operating in national or international waters due to substantial technical differences.

Unlike for passenger, a sensitivity analysis investigating the response of modal shift to variations in the adopted substitution elasticities (Section 3.2, Paper **IV**) reveals that freight modal shift is closer to saturate. In particular, in 2050, freight modal shift saturates at 27,866 Mtkm (corresponding to 11,580 Mtkm additional demand shift with respect to the Base scenario).

6.4 DISCUSSION AND FUTURE RESEARCH

This section, first comments upon the pros and cons and possible improvements of the developed methodology (Section 6.4.1), and then criticizes its specific application in the case study addressed in this chapter while providing topics for dedicated future research (Section 6.4.2).

6.4.1 ELASTIC TRANSPORT MODAL SHIFT

As mentioned at the end of Chapter 5, the developed methodology for emulating transport modal shift into BU optimization E4 models have several advantages compared to alternative methods. Its compactness, the low data requirements and the low impact on computational time make the substitution elasticities a preferable approach to model transport modal shift in large LP resulting from representing multi-regional models in TIMES. In addition, a comparison of the modal shift obtained in this analysis with potentials estimated by alternative modelling methods and studies addressing the same topic for the Nordic countries reveals similar results, strengthening the validity of the methodology. However, given the scarcity of studies addressing the same topic and geographical scope, systematic validation is difficult.

In the Norwegian freight sector, technical modal shift potential is estimated at between 5 and 7 million tonnes per year by [125], which corresponds to 2000–2800 Mtkm assuming an average distance of 400 km. The range obtained for Norway across the time horizon (1800–3800 Mtkm) is comparable to this potential. In ref. [136], freight modal shift is analysed for Norway in 2030 under different policy instruments aiming at stimulating a shift from road to rail and sea transportation. In most of the scenarios presented, road transport decreases in terms of transport performance by an amount within the range 813–3458 Mtkm, while rail increases by an amount within the range 686–6000 Mtkm. The sea transport contribution to modal shift varies across scenarios, its transport performance variation ranges from +1975 Mtkm to –2429 Mtkm depending on the policy instrument implemented. The results for freight modal shift obtained with TIMES-Nordic in the Base scenario fall in the range obtained by [136]. Indeed, in 2030 in Norway, truck demand decreases by 1486 Mtkm, while rail demand increases by 1757 Mtkm. A comparison for sea transport is more arduous given the different role played across the scenarios presented by [136], though the demand decrease obtained with TIMES-Nordic for this mode (271 Mtkm) also falls within the range identified by [136].

For the inland Danish passenger sector, the total shift obtained in 2050 is around 1300 Mpkm, which is also comparable to the modal shift range obtained by [20] within different scenarios (1000–10,000 Mpkm). On the other hand, ref. [137] obtained a much wider passenger modal shift range in 2050 for Denmark across a number of “pull” and “push” policy scenarios.

The compactness and simplicity of using substitution elasticities to model transport modal shift comes at a cost, the severe simplification of the described phenomenon. First of all, the magnitude of modal shift achievable is limited only to such cases where modal shift can occur within a 100% change relative to the original modal travel demands. Moreover, in passenger transport, consumer modal choice is driven by multiple factors, such as level of service (LoS) parameters like travel time, travel cost and travel comfort, which characterise every mode differently. In addition, consumers belonging to different socio-economic and demographic groups (age, gender, income, etc.) evaluate those factors differently, when making transport choices [61]. In the proposed methodology, all these dynamics are reduced to the values adopted for σ_k, and the modal shift levels are obtained from the perspective of a central decision-maker (by minimizing the total system costs) instead of from the consumers’ perspective.

For instance, within an aggregate k, each mode is considered a perfect substitute of the others regardless its speed, while the substitution mechanism is regulated only by the elasticity values. However, in reality people are willing to spend a certain amount of time travelling per day [138], whose value appears to be similar across several dimensions such as geography or income classes. This constraint is not included in the actual modelling framework. This lack can potentially lead to unrealistic results especially when the substitution involves modes with large differences in travel speed, e.g. in the *XS* and *S* aggregates where walk substitutes car trips in the length range from 0 to 25 km. This limitation could be overcome by including the concept of travel time budget as done by [20].

Moreover, the spatial dimension adopted to describe the transport sector is quite aggregated, e.g. no differentiation between urban and non-urban areas is modelled. However, modal adoption is dependent on public transport availability/accessibility, which differs across different geographical areas. A possible improvement could be to disaggregate the spatial dimension in order to capture these differences.

Lastly, since long-term own-price elasticities are usually provided in the literature for each mode, the possibility to characterise the substitution elasticity σ_k in every aggregate *k* per demand segment *i*, which is possible with the elastic demand formulations available in TIMES models [123], represents an interesting and easily implementable improvement. In the methodology presented, a representative substitution elasticity, obtained as weighted average of modal elasticities weighted with their respective demands, is adopted for each aggregate *k* (Section 6.2.1). The declaration of a specific $\sigma_{k,i}$ for each demand segment would remove this aggregation step and improve modal representation.

6.4.2 TIMES-NORDIC ANALYSIS

Concerning the specific application of this methodology in TIMES-Nordic, the analysis presents some shortcomings, though none directly related to the methodology itself. The identified shortcomings are commented on their possible effects on the results and suggestions for improving the analysis are discussed.

One of the aims of Paper **IV** is to identify the proper elasticities type (from available transport literature) to be used in the developed methodology considering the modelling environment adopted (TIMES-Nordic and the TIMES framework in general). The outcome of this analysis is summarised in Section

6.2.1, where long-term own-price elasticities are presented as the most suitable transport elasticity type among the categories available in the literature. This task has been prioritized over finding the most recent and relevant elasticity data. Indeed, for some of the modes, the modal elasticities assumed do not belong to the suggested category. This required a number of assumptions and calculation steps to align the available data with the modelling framework. These assumptions are arguable from different perspectives and the calculation steps adopted should not be regarded as a recommended procedure to follow when applying the developed methodology. However, if potential users adopts the suggested elasticities type, they would not need to apply the approximations presented. Moreover, the model is usually quite sensitive to the elasticity values adopted; this has been shown in Paper **III** and Paper **IV** in dedicated sensitivity analyses. Therefore, it is crucial that a potential user pays particular attention in the choice of these model inputs. For this reason, some of the approximations/assumptions carried out are discussed hereafter in a critical way.

First of all, the elasticity for car obtained from [133] is multiplied by a factor of three in order to obtain a long-term elasticity value. This approximation is carried out in light of general observations outlined by review studies on transport elasticities, which claim that long-term elasticities are usually two to three times larger than short-terms ones (e.g. [129] and [132]). The same applies for walk, bike, moped and moto. However, elasticity values provided by [133] are already semi-long-term elasticities, thus this approximation is questionable. Since the mode car represents the transport mean with the highest mobility demands defined in the passenger inland transport sector in TIMES-Nordic, the adoption of a lower elasticity value for this mode would entail a lower σ_k in the different distance categories, which would lead to a lower modal shift in the passenger sub-sector compared to the presented results. For instance, if the elasticity for car, walk, bike, moped and moto obtained based [133] would not be scaled up with the multiplicative factor of three, σ_k would roughly halve their values (see Appendix B for details). However, this would represent an extreme case where the modal elasticities provided by [133] are assumed representative also for the long-term case, while pure long-term elasticities would probably be slightly higher, though this example shows the large impact of the car elasticity value on the computed substitution elasticities.

The freight ship elasticity is adopted from the Belgian study [134]. This study provides elasticities representative for inland waterways shipping. However, the freight shipping demands defined in TIMES-Nordic are predominantly representative for open sea shipping (e.g. occurring in the Baltic and the North Sea), thus the assumed modal elasticity represents a questionable assumption. The Danish study [139] reveals much lower elasticities for freight sea transport, about an order of magnitude lower regardless the type of goods transported. In particular, ref. [139] provides freight elasticities by applying a weighted logit freight mode-choice model for the Oresund region. Also in this case, ship is the transport mean with the largest freight demands defined in TIMES-Nordic, thus the adoption of a lower elasticity value for this mode would entail for a substantial decrease in modal shift due to the resulting lower σ_k. In particular, when assuming an average direct elasticity for freight ship from [139], σ_k would, also in this case, halve their values (see Appendix B for details).

These insights suggest that the modal shift results presented in Section 6.3 are probably overestimated due to the approximations discussed above.

Besides, the elasticities assumed for the remaining freight modes (truck and rail) are adopted from an older study [128], which focuses mainly on the United States as a geographical scope. As pointed out by [139], European freight transport seems relatively inelastic with respect to the choice of mode compared to studies conducted in the United States, though the assumed values are similar to other elasticities provided by more recent studies addressing other geographical scopes (e.g. Europe and the Nordic countries) [134,140,141]. However, the modal elasticities assumed in this PhD thesis generally derive from heterogeneous transport literature focusing on different countries such as the United Kingdom, the United States, Belgium, Denmark, etc. instead of focussing exclusively on the studied countries. The adoption of recent elasticities representative for the specific countries under study is strongly recommended. Lastly, substitution elasticity could be defined differently for each year t of the time horizon T. However, this possibility has not been investigated in this PhD thesis.

A well-balanced technological description across transport modes is crucial when introducing modal competition. The inclusion of alternative fuelled (e.g.

hydrogen, gas, methanol or ammonia) ships could overturn the role of this mode in freight modal shift. The same applies to trucks, whose technological descriptions are limited to diesel blending and gas ICEVs and BEVs. Indeed, hydrogen fuel cell and hybrid trucks are also considered promising technologies, especially if accompanied by electrified roads [5]. This is particularly relevant in the Nordics, where the electricity system is expected to accommodate a major amount of renewables in the future (Appendix B of Paper **IV**). An exhaustive representation of modal technologies could enrich the scenario analysis with additional insights into the topic.

Moreover, transport infrastructure is not included in TIMES-Nordic, even though, especially for rail, it is considered one possible impediment to modal shift [126]. Elasticity values capture the effect of the existing infrastructure and its capability to accommodate change in transport demand only indirectly and partially. Therefore, when modal shift involves a large variation in modal demands, possibly reaching infrastructure saturation, its direct inclusion in the modelling framework is recommended (as done e.g. by [20]). In addition, the transport modal shift potentials adopted in the case study analysed are assumed, for simplicity reason, arbitrarily equal for every mode, though they can be estimated based on modal substitution considerations such as done in Paper **III**, and can also be used to embody infrastructure saturation potentials.

Within the boundary conditions assumed in the analysis carried out, modal shift is claimed to be a cost-effective measure to reduce CO_2 emissions, indeed it entails for a lower total system cost compared to the inelastic case. However, as mentioned above, the resulting modal shift is obtained while neglecting the transport infrastructure (e.g. road and rail networks). Therefore, all the cost related to such infrastructure (due to e.g. maintenance or potential expansion resulting from an increase in transport demand) are also neglected and thus not considered in the optimization. However, the explicit inclusion of these costs in the model could affect modal shift, though this is very dependent on how the infrastructure is modelled and on the level of detail. Let us assume that the existing infrastructure capacity is enough to accommodate the mobility demands in the reference case. If a demand increase in the elastic case would require additional transport infrastructure capacity, compared to the reference case, the additional investment cost could limit the attractiveness of increasing such demand. Moreover, the volume-preserving condition would force the model to compare such dynamics across all modes, thus, in the case of large modal demand variations (requiring expansions in infrastructures), investment costs would indirectly be put in competition during the optimization. Therefore, in the case transport infrastructure is included in the model, this should be done for all modes to avoid unfair comparisons.

In light of the above, the obtained modal shift levels can be considered a cost-effective mitigation measure only within the assumed boundary conditions, which exclude any reflections in terms of potential effects/interactions on/with transport infrastructure. Indeed, when considering such modes with a large demand increase (such as rail), the claimed cost-effectiveness could be disproved in reality due to the potential additional costs (resulting from infrastructure expansion) not captured by the model.

It is important to remember that the modal shift levels presented in Section 6.3 are obtained with a CO_2 tax based on the marginal abatement costs resulting from the CNS [13]. Such marginal abatement costs are representative of the electricity sector, though the transport sector is considered more challenging to decarbonise. Therefore, further research could estimate modal shift levels by assuming higher CO_2 tax levels or by including a constraint imposing a limit on the transport emissions levels over the years lower than the trends obtained.

Lastly, concerning further research for purposes of freight transport modelling, the inclusion of additional modal technologies (such as different freight ships and trains) differentiated in terms of size, load capacity, mileage and typical deployment (type of good transported) together with a characterization of transport demands in terms of good types, could enrich the modal shift analysis. Indeed, different good types have specific requirements/issues related to their delivery, which can range from perishability to safety, technical feasibility such as high load capacity (e.g. ore or crude oil) and others. Capturing these differences in market segmentation in the modelling framework could lead to a more realistic representation of competition between modes when enabling modal shift, rather than simply assuming that each mode is a perfect substitute for the others. Moreover, as shown by [139], elasticities for freight differ by commodity type transported, such a description would enable the declaration of a specific modal elasticity depending on the good transported, which would lead to more realistic results. On the other hand, this improvement would require profound changes in the modelling structure and extra data.

6.5 ANALYSIS VALIDATION

Since a systematic validation of the results obtained in Section 6.3 is difficult due to the scarce literature on the topic addressing the specific geographical area studied, a few additional analyses are carried out to test the solidity of the obtained results. The additional analyses are not part of any papers included in this PhD thesis, instead they are presented here for the first time. In Section 6.5.1, a MNL model is used to calculate modal share variations between the reference case and the Base scenario. Such variations are compared with the ones obtained with TIMES-Nordic. In Section 6.5.2, two analyses are carried out. First, the implied substitution elasticities resulting from TIMES-Nordic results in the Base scenario are calculated and compared with the declared values as a sanity check (Sub-section 6.5.2.1). In the second analysis, the implied cross-price elasticities resulting from the introduction of a known modal price shock in TIMES-Nordic are calculated and compared with transport literature (Sub-section 6.5.2.2).

6.5.1 MNL MODEL ANALYSIS

MNL models have been used for long time to assess modal choice and shares worldwide (see Section 3.3.1), representing one of the most reliable tools for this aim. Therefore, a simple MNL model is developed within this PhD thesis to support a validation analysis of the modal shift levels obtained with TIMES-Nordic. For simplicity reason, this analysis is carried out only for the Danish inland passenger sector. Moreover, the MNL model is estimated separately for Denmark East (DKE) and Denmark West (DKW), following the geographical description captured by TIMES-Nordic.

In Eq. (6.1), the utility form $U_i(t)$ used to estimate the MNL model is shown for an arbitrary year t:

$$\begin{gathered} U_i(t) = V_i(t) + \varepsilon_i \\ where \quad V_i(t) = \alpha_i + \beta \cdot TC_i(t) \end{gathered} \tag{6.1}$$

In Eq. (6.1), as in the previous chapters, the index i identifies the mode, while α_i are the alternative-specific constants, the total cost $TC_i(t)$ is the explanatory variable, which represents the cost of adopting mode i in a given year and its units are [euro 2015/pkm]. The term ε_i represents the error resulting from assuming that modal choice is affected only by the attributes included in the utility function formulated, while $V_i(t)$ is the deterministic part of the utility function. The utility function is unit less, which means that so are α_i and β has units of [pkm/euro 2015]. Moreover, a pivotal assumption in MNL models is that the choice set must satisfy three criteria: a) alternatives are mutually exclusive, b) choice set is exhaustive (all alternatives are considered) and c) the number of alternatives is finite. This set of assumptions holds in both TIMES-Nordic and in the developed MNL model.

The total cost $TC_i(t)$, characterising each mode in every year, is the sum of different quantities that are heterogeneous between private and public modes of transport as shown in Eq. (6.2), where PR represents the subset of private modes and PB of public transport modes.

$$TC_i(t) = \begin{cases} FC_i(t) + NFC_i(t) + intC_i(t) & for\ i \in PR \\ TP_i(t) + intC_i(t) & for\ i \in PB \end{cases} \tag{6.2}$$

In particular, $FC_i(t)$ is the fuel cost, $NFC_i(t)$ is the non-fuel cost (including operation and maintenance and investment cost) and $intC_i(t)$ is the intangible cost, while $TP_i(t)$ is the ticket price for public means of transport. Obviously, the units of all quantities presented in Eq. (6.2) are [euro 2015/pkm].

The fuel costs $FC_i(t)$ and the non-fuel costs $NFC_i(t)$ are obtained from the TIMES-Nordic results for the reference case. $NFC_i(t)$ are calculated for each mode and each year as weighted average across the different technologies composing the mix, using as weights the mobility demands supplied. Moreover, since investment costs are declared in TIMES-Nordic per vehicle, they are firstly annualised (based on the life time assumed) and then they are normalised by dividing by the occupancy factor and the annual mileage, while in the case of operation and maintenance costs, which are declared per activity unit, they are normalised by diving by the occupancy factor.

Concerning the $FC_i(t)$ terms, for each mode and each year, the shadow price (expressed in [euro 2015/GJ]) of each fuel consumed by each technology composing the mode is divided by the modal occupancy factor and by the technology efficiency (expressed in [vehicle*km/GJ]) in order to obtain a technology fuel cost per pkm (expressed in [euro 2015/pkm]). Then a weighted average of the technology fuel costs is calculated across the fuel types/technologies as in the $NFC_i(t)$ case to obtain the $FC_i(t)$.

The intangible costs $intC_i(t)$ are kindly provided by the authors of ref. [61], who calculate these quantities for Denmark East and West disaggregated into different geographical areas, namely “urban”, “sub-urban” and “rural”, and into population income classes, namely “very low”, “low”, “medium” and “high”. The $intC_i(t)$ terms represent non-monetary costs perceived by consumers when choosing a means of transport, which include level of service parameters such as modal travel time or waiting time for public transportation. In particular, $intC_i(t)$ are calculated for each mode by multiplying a generalised travel time (heterogeneous across geographical areas and expressed in [h/km]) with the value of time (heterogeneous across income classes). The intangible costs set assumed from [61] is the “urban - low”. The “urban” area is chosen for simplicity reasons, while the income class “low” is chosen since the Danish average income level falls within this category. In particular, the value of time assumed within this group is 87,6 dkk/h and is assumed constant along the times horizon, even though this quantity could be subjected to variations in the future.

The ticket prices $TP_i(t)$ for public transport are also provided by the authors of ref. [61]. Since the modes moto, moped and coach are not included in the analysis carried out by [61], the intangible costs for such modes are calculated for this analysis through some assumptions. For moto, intangible costs are assumed equal to the ones for car, the same applied for moped but they are adjusted assuming 20% lower modal speed than car. For coach, intangible costs are assumed equal to bus but they are adjusted assuming 20% higher modal speed compared to bus, while ticket price for coach are assumed 50% lower than bus. Moreover, for simplicity reasons, for private modes ownership taxes and parking fees are not considered in this analysis, while fuel taxes are neglected since they are not present in TIMES-Nordic.

In Table 6.3, the alternative-specific constants α_i and the parameter β estimated for the MNL model are presented:

Table 6.3. *MNL model parameters estimated for Denmark East and Denmark West.*

Parameter	Denmark East (DKE)	Denmark West (DKW)
α_{car}	-7.024	-5.839
α_{moto}	-12.255	-10.924
α_{moped}	-14.052	-12.580
α_{bus}	-8.437	-8.332
α_{coach}	-8.526	-8.350
α_{metro}	-10.327	
$\alpha_{light\ rail}$	-9.042	
α_{train}	-8.593	-7.927
α_{bike}	-7.754	-7.043
α_{walk}	0	0
β	-0.415	-0.389

The model parameters α_i and β are estimated through maximum likelihood estimation by imposing to the MNL model to replicate the modal shares in the BY (2010). The obtained model is then calibrated to reproduce the modal shares in 2050 for the reference case by changing the alternative-specific constants (again through maximum likelihood estimation). Moreover, since only *N*-1 alternative-specific constants can be estimated, α_{walk} is assumed equal to zero for both DKE and DKW. It is worth noticing that the cost coefficients β are negative, which means that total cost $TC_i(t)$ has a negative effect on the probability of choosing a specific mode.

After estimating the MNL model, the probability of choosing a specific mode alternative (*i*) can be computed for the different years *t* as shown in Eq. (6.3) (where *j* is the index counting over the different alternatives):

$$P_i(t) = \frac{e^{(V_i(t))}}{\sum_j e^{(V_j(t))}} = \frac{e^{(\alpha_i + \beta \cdot TC_i(t))}}{\sum_j e^{(\alpha_j + \beta \cdot TC_j(t))}} \qquad (6.3)$$

In Fig. 6.6, the modal shares obtained with the MNL model are compared with the ones defined in TIMES-Nordic for the reference case in the years 2010 and

2050 and for both regions. Besides minor variations, the MNL model reproduces well the modal shares in both years.

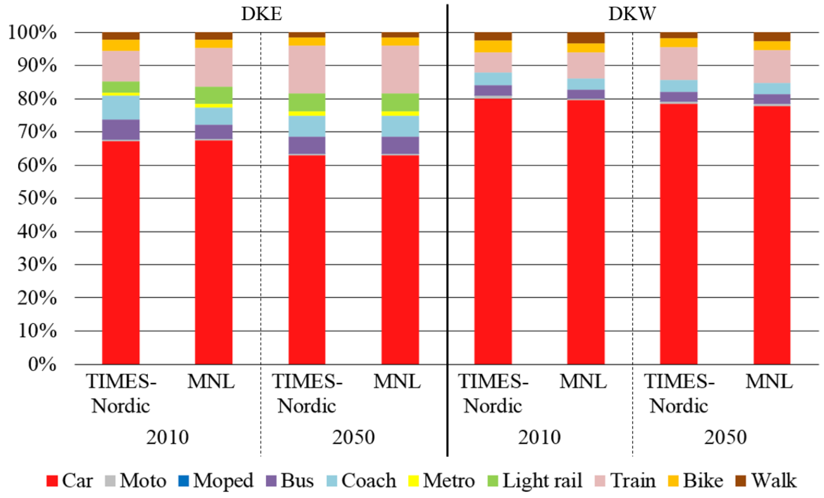


Fig. 6.6. *Modal shares in 2010 and 2050 for the inland passenger transport sector in Denmark East (DKE) and Denmark West (DKW) defined in TIMES-Nordic and calculated with the MNL model for the reference case.*

At this point, the modal shares along the time horizon can be calculated with the MNL model for the Base scenario analysed in Section 6.3. The $TC_i(t)$ terms for all modes are expanded in order to include the CO_2 tax contribution as shown in Eq. (6.4):

$$TC_i(t) = \begin{cases} FC_i(t) + CO_2Tax_i(t) + NFC_i(t) + intC_i(t); & for\ i \in PR \\ TP_i(t) + CO_2Tax_i(t) + intC_i(t) & for\ i \in PB \end{cases} \tag{6.4}$$

For each mode and each year, the $CO_2Tax_i(t)$ term is calculated by multiplying the CO_2 tax level by the modal emissions (expressed in [tonne/pkm]). Modal emissions along the time horizon are obtained from TIMES-Nordic results (reference case), namely, for a specific year, the fuel consumption of each technology composing a mode is multiplied by the emission coefficients of the respective fuel to obtain modal technology emissions. Modal emissions are then calculated by summing all the modal technology emissions and then dividing by the modal mobility demand supplied. As it can be noted in Eq. (6.4), the $CO_2Tax_i(t)$ terms are included also for public transport modes, assuming that such additional cost would be added to the ticket price. The probability of choosing a specific mode i can now be calculated for the Base scenario by applying Eq. (6.3) with the new $TC_i(t)$ terms (Eq. (6.4)).

In Fig. 6.7, modal shares for DKE and DKW obtained with the MNL model and with TIMES-Nordic are compared for the reference case (*R*) and the Base scenario (*B*) in the years 2030, 2040 and 2050. It should be noted that the modal shares shown for TIMES-Nordic in the Base scenario are the ones obtained with elastic modal shift (TIMES-NordicEMS following the nomenclature adopted in Section 6.3). The modal shares obtained with the MNL model almost do not vary between the two scenarios, while for TIMES-Nordic the variation is much higher (details on the modal mobility demand variations can be consulted in Fig. 6.4 in Section 6.3).

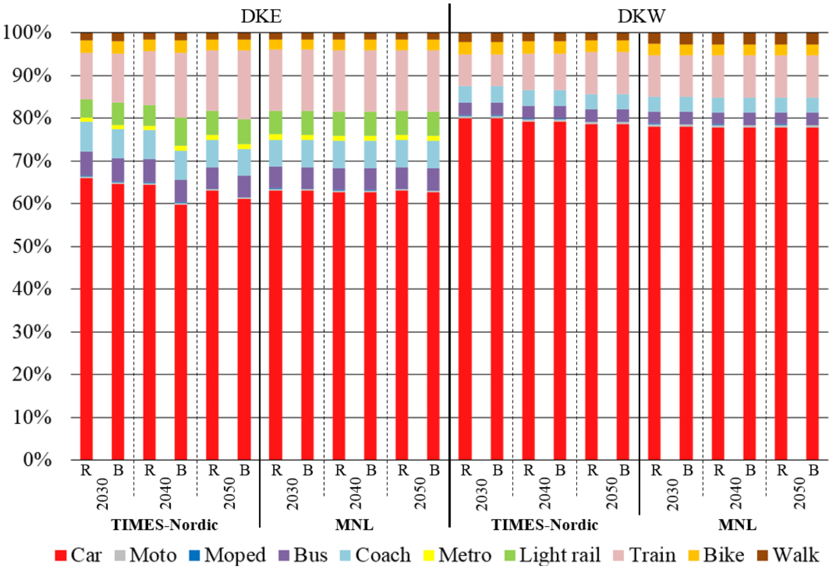


Fig. 6.7. *Modal shares in 2030, 2040 and 2050 for the inland passenger transport sector in Denmark East (DKE) and Denmark West (DKW) obtained with TIMES-Nordic and the MNL model in the reference case (R) and in the Base scenario (B)*. *The modal shares shown for TIMES-Nordic in the Base scenario are obtained with elastic modal shift.*

However, after taking a closer look at the variations in modal shares obtained with the MNL model between the two scenarios across the years, similar trends to the ones obtained with TIMES-Nordic, can be observed. In Fig. 6.8, the variations (obtained through subtraction) in modal shares between the Base scenario and the reference case are presented for both models, both regions and for the years 2030, 2040 and 2050.

For both DKE and DKW, the car is substituted mainly by rail modes (such as train, light rail and metro) and non-motorised modes in both models along the whole time horizon. Bus and coach play a different role between the two models, in TIMES-Nordic they do not vary their shares at all, while in the MNL model they increase their shares in both regions. Moreover, the modal share variations increase over the years in both models due to the increasing CO_2 tax levels, the only exception is in 2050 where modal shift shrinks in TIMES-Nordic compared to the previous years. As explained in Section 6.3.2, the modal shift shrink in 2050 is due to the high penetration of gasoline blending ICE cars with a high share of bioethanol consumption in the reference case, which reduces the effect of the CO_2 tax in stimulating variations in the shadow prices of car modality demands (compared to the previous years). This trend takes place in DKE, where it is also combined with a partial electrification of the car fleet in the Base scenario. Instead, in DKW there is a large penetration of BE cars in the Base scenario, which reaches its peak in 2050. This strong electrification is driven by the low electricity price in DKW (the lowest across all regions). Therefore, in 2050 in the Base scenario, the model “prefers” to invest in BE cars rather than shifting car demands to other modes in both regions. This trend cannot be seen in the MNL model since the modal total costs $TC_i(t)$ are calculated starting from the reference case technology mix, which is fixed between the two scenarios.

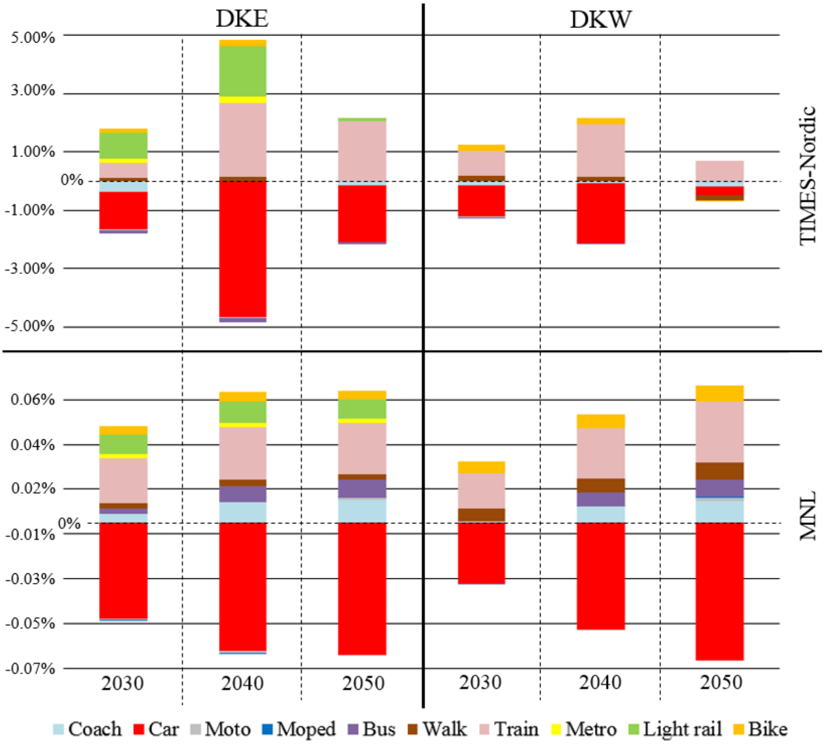


Fig. 6.8. *Modal share variations (obtained through subtraction) in 2030, 2040 and 2050 for the inland passenger transport sector in Denmark East (DKE) and Denmark West (DKW) between the Base scenario and the reference case and obtained with TIMES-Nordic and with the MNL model.*

Besides the year 2050, the substitution trend is very similar between the two models, though its magnitude is much lower in the MNL model compared to TIMES-Nordic. In particular, the maximum modal share variation achieved in TIMES-Nordic is around 5%, while in the MNL model is around 0.06%, almost two orders of magnitudes lower. This is a further evidence that some modal elasticities (e.g. for car) used as input in TIMES-Nordic are overestimated compared to reality. Lower modal elasticities would entail a lower modal shift across the years, which in turn would likely result in modal shares variations closer to the ones obtained with the MNL model.

Moreover, the results obtained with the MNL model suggest that the CO_2 tax levels adopted might be not enough to stimulate a significant modal shift. This underlines the need for further research focusing on applying higher CO_2 tax levels as suggested in Section 6.4.2.

Lastly, it is worth noticing that the "Independence of Irrelevant Alternatives" (IIA) property, resulting from the mathematical structure of MNL models, does not hold in TIMES-Nordic. The IIA property states that the relative share between the probabilities of two alternatives will remain unchanged irrespectively of the utility of other alternatives [142]. In TIMES-Nordic, the substitution across transport modes is obtained by minimizing the total system costs while satisfying the volume-preserving condition besides the other constraints defined. Considering three transport modes and an increase in the travel cost of mode three compared to a reference case, there is no constraint imposing that the ratio of market shares of the other two alternatives should be kept constant after substitution (compared to the reference case). The absence of this assumption in TIMES-Nordic compared to the MNL model contributes to the discrepancies between the modal shares variations obtained with the two models.

6.5.2 IMPLIED ELASTICITIES

In this Section, first a simple analysis is carried out to investigate if the implied elasticities resulting from TIMES-Nordic results in the Base scenario are in line with the values declared (Section 6.5.2.1). Moreover, only direct elasticities are declared as inputs to the model, while the substitution mechanism is guaranteed by the volume-preserving condition. Therefore, an ulterior simple analysis is carried out to check if the implied cross-price elasticities resulting from the introduction of a known modal price shock in TIMES-Nordic are in line with the transport literature (Section 6.5.2.2). For brevity reasons, the analysis presented in this section only tackle the passenger sub-sector.

6.5.2.1 Implied substitution elasticities

First of all, the implied (*imp*) substitution elasticities in the Base scenario for each mode are calculated for each demand aggregate *k* knowing the demand and the shadow price change between the elastic (*el*) and the reference case (*0*) by applying Eq. (6.5):

$$\frac{DM_{k,i}^{el}(t)}{DM_{k,i}^{0}(t)} = \left(\frac{p_{k,i}^{el}(t)}{p_{k,i}^{0}(t)}\right)^{\sigma_{k,i}^{imp}(t)} \quad \rightarrow \quad \sigma_{k,i}^{imp}(t) = \frac{\ln(\frac{DM_{k,i}^{el}(t)}{DM_{k,i}^{0}(t)})}{\ln(\frac{p_{k,i}^{el}(t)}{p_{k,i}^{0}(t)})} \qquad (6.5)$$

It should be noted that Eq. (6.5) is applied by the model in its linearized form (as described in Chapter 5). However, the number of linearization steps adopted led to a good approximation of the non-linear form. Therefore, adopting Eq. (6.5) is a fair assumption. Moreover, the substitution elasticity σ_k, declared for each aggregate *k*, is the same across the different modal demands composing the aggregate. The reason why the implied elasticities $\sigma_{k,i}^{imp}(t)$ appearing in Eq. (6.5) are dependent on the index *i* (identifying the mode) is because, for each mode, they are calculated from its specific modal demand and shadow price variations.

The mode firstly analysed is car, since it is the mode most affected by the CO_2 tax and thus driving the modal substitution. For each year, the substitution elasticity is calculated for each region and each distance class *k* by applying Eq. (6,5). Then, for each *k*, a weighted average elasticity is calculated across regions using as weights the car mobility demands defined in each region in the reference case. The average implied elasticities so obtained for car $\bar{\sigma}_{k,car}^{imp}(t)$ are presented in Table 6.3 for 2040 and 2050 together with the average between the two years and the elasticities declared as inputs in the model σ_k. Moreover, an average substitution elasticity (Avg.) is also shown, which is calculated as a weighted average across distance classes (*k*) using as weights the car mobility demands defined in the reference case for that specific year. Please note that since σ_k are constant across the time horizon, its weighted average across aggregates *k* is calculated using as weights the car mobility demands defined in 2020.

Table 6.3*. Average implied substitution elasticities for car in TIMES-Nordic in the Base scenario for each aggregate k (resulting from demand and shadow price change between the elastic and the reference case) compared with the substitution elasticities declared. Values are provided for 2040 and 2050 together with the average between these two years and the weighted average across distance classes (k).*

$\boldsymbol{k}$	$\boldsymbol{\sigma_k}$ Declared	Average $\boldsymbol{\bar{\sigma}^{imp}_{k,car}}$	$\boldsymbol{\bar{\sigma}^{imp}_{k,car}(2040)}$	$\boldsymbol{\bar{\sigma}^{imp}_{k,car}(2050)}$
XS	-0.82	-0.85	-0.88	-0.81
S	-1.05	-0.67	-0.68	-0.65
M	-1.26	-0.71	-0.84	-0.58
L	-1.59	-1.88	-2.08	-1.68
Avg.	**-1.33**	**-1.24**	**-1.36**	**-1.12**

As seen in 2040 and 2050 the $\bar{\sigma}^{imp}_{k,car}(t)$ are slightly lower than the declared values for the *S* and *M* categories, while for the *L* category they are slightly higher. These deviations from the declared values are expected as they are the result of a complex dynamic and a few approximations. Similar deviations are observed also for the other modes participating to the substitution. In Table 6.4, average implied substitution elasticities calculated with the same approach applied for car (using Eq. (6.5)) are presented for the modes contributing the most to modal shift. Please note that, for a specific mode, the weighted average across regions discards the contributions of such regions where the mode does not participate to the substitution.

***Table 6.4**. Average implied substitution elasticities for different modes in TIMES-Nordic in the Base scenario for each aggregate k (resulting from demand and shadow price change between the elastic and the reference case) compared with the substitution elasticities declared. Values are provided for 2040 and 2050 together with the average between these two years.*

Mode	$\boldsymbol{k}$	$\boldsymbol{\sigma_k}$ Declared	Average $\boldsymbol{\bar{\sigma}^{imp}_{k,i}}$	$\boldsymbol{\bar{\sigma}^{imp}_{k,i}(2040)}$	$\boldsymbol{\bar{\sigma}^{imp}_{k,i}(2050)}$
Bike	XS	-0.82	-0.84	-1.05	-0.62
	S	-1.05	-1.11	-1.17	-1.05
Metro	XS	-0.82	-0.68	-0.70	-0.66
	S	-1.05	-0.95	-0.92	-0.97
Train	S	-1.05	-0.97	-0.97	-0.97
	M	-1.26	-1.14	-1.32	-0.97
	L	-1.59	-1.56	-1.64	-1.49
	X	-0.82	-0.89	-0.91	-0.87

Light rail	S	-1.05	-1.38	-1.25	-1.51
	M	-1.26	-1.47	-1.29	-1.66
Walk	X	-0.82	-0.78	-0.79	-0.77
	S	-1.05	-0.96	-0.95	-0.97

For some modes presented in Table 6.4, the average implied substitution elasticities vary largely compared to the declared ones (e.g. light rail). These deviations are partially due to the step-wise approximation adopted to linearize the demand response. However, for a specific mode, its demand decrease/increase is not only due to the increase/decrease of its supply cost function (as it would be in an own-price elastic scenario analysis) but it takes into account also the variations of the other modes demands shadow prices together with their capability to adapt to such demand variations (volume-preserving condition). Such dynamics together with additional constraints as the travel patterns can amplify these deviations even more. However, besides these deviations, the elastic response is overall roughly respected and such constraints are necessary to guarantee realism in modal substitution.

Lastly, the percentage change in shadow prices $\frac{p_i^{el}(t)-p_i^0(t)}{p_i^0(t)}$ between the elastic and the reference case is calculated for all modes participating to modal shift in the Base scenario, then a weighted average is calculated across regions and distance classes *k* using as weights the demands defined in the reference case. The average percentage change in shadow prices are presented in Table 6.5 for the years 2040 and 2050 together with the average between the two years.

Table 6.5. *Average percentage change in shadow prices between elastic and the reference case for different modes in TIMES-Nordic. Values are provided for 2040 and 2050 together with the average between these two years.*

Mode	$\overline{\left(\frac{p_i^{el}(2040)-p_i^0(2040)}{p_i^0(2040)}\right)}$	$\overline{\left(\frac{p_i^{el}(2050)-p_i^0(2050)}{p_i^0(2050)}\right)}$	$\overline{\left(\frac{p_i^{el}-p_i^0}{p_i^0}\right)}$
Bike	-4.9%	-1.6%	-3.3%
Bus	0.5%	-0.9%	-0.2%
Car	3.2%	3.2%	3.2%
Coach	0.7%	1.4%	1.1%

Moped	3.7%	-1.6%	1.0%
Moto	4.2%	-0.3%	1.9%
Metro	-7.9%	-9.3%	-8.6%
Train	-12.2%	-12.0%	-12.1%
Light rail	-15.6%	-4.7%	-10.1%
Walk	-12.2%	-11.5%	-11.9%

In general, those modes whose shadow prices increase in the elastic case compared to the reference case (shown in Table 6.5) decrease their demands and vice versa, which is in line with the equations applied. However, particular attention should be paid when analysing the meaning of the shadow prices calculated by the model in the elastic case. For a specific demand commodity, the shadow price represents the marginal change of the objective function per unit increase of its demand level or better per unit increase of the right-hand side of the demand commodity balance equation. Since the left-hand side of the commodity balance equation generally describes the difference between production and consumption, the additional demand unit may be covered by an increase in production or by a decrease in consumption. In the first case, the shadow price is determined by activities on the supply side of the demand commodity, while in the latter case saving measures on the demand side of the commodity are setting the shadow price [143]. In addition, the volume-preserving condition holds also in this case, e.g. if the model identifies as optimal to increase the production of the demand commodity by one unit, the calculated shadow price would include also the total cost of reducing by one unit another demand commodity among the ones included in the aggregate.

The meaning of the shadow price in the elastic scenario is slightly more complex compared to the inelastic case since the objective function includes also cost/gain terms representing the loss/increase in consumer surplus. Often, shadow prices can be used to identify the marginal cost to supply an additional unit of a specific demand commodity (unless the equilibrium happens in a discontinuity of the supply cost curve). However, in this case the shadow price is identified by the trade-off of several quantities, which do not represent only marginal change in supply cost. For this reason, the shadow price changes presented in Table 6.5 should not be interpreted as representative of change in marginal cost to supply the modal mobility demands between the Base scenario and the reference case.

For instance, the demand shadow prices of those modes not largely affected by the CO_2 tax (such as train, metro and light rail) are lower in the elastic case respect to the reference case (Table 6.5). Such modes increase their demands in the elastic case despite their supply cost function has remained almost unchanged compared to the reference case. Their reduction in shadow prices means that an additional unit of demand would impact the objective function in a lower way compared to the reference case. Indeed, thanks to the substitution mechanism the model can increase the demands of these modes in order to reduce the demands of those modes whose supply cost function has shifted up compared to the reference case (while taking into account also the variations in consumer surplus). In other words, it means that modes with lower shadow prices (compared to the reference case) contributes overall to minimize system cost and maximize consumer surplus in the elastic case. The opposite argumentation can be elaborated for such modes whose shadow prices increase in the elastic case compared to the reference.

In case a possible user of the elastic modal shift methodology would like to check the effect of the policy under study (represented in this analysis by the CO_2 tax) on the marginal modal supply cost, a possibility is to compare the modal demands shadow prices changes between the inelastic and the reference case. However, such costs might not be representative for the elastic case, since the equilibrium between supply and demand is reached with different demand levels compared to the elastic case. Therefore, in general such analysis would only provide a qualitative insight.

6.5.2.2 Implied cross-price elasticities

In this section, the implied cross-price elasticities resulting from the modal substitution triggered by a known price shock affecting a specific mode are calculated and compared with the transport literature. In particular, the car travel cost is increased by 10% in TIMES-Nordic (with elastic modal shift) and the effect on the mobility demands variations of the other modes is analysed. In other words, the same analysis as the one carried out in Section 6.3 for the Base scenario is carried out in this section. However, instead of using a CO_2 tax to trigger modal substitution, a price shock on the travel cost for cars is adopted. Besides this, all the remaining assumptions and boundary conditions are kept equal to the Base scenario (e.g. substitution elasticities and modal shift potentials). From now on, the scenario including the price shock on car travel cost will be called “Price shock”.

Two different simple approaches are adopted to increase car travel cost by 10%. In the first approach, the operation and maintenance costs (declared per activity unit) of car technologies (existing and new ones) are increased by 10% in the Price shock scenario compared to the reference case. Moreover, since increasing fuel cost by 10% only for car technologies is challenged by the assumed modelling architecture, the efficiency of existing and new car technologies is reduced by 10% in the Price shock scenario compared to the reference case. This is a handy but rough method to emulate a 10% increase in fuel cost for cars, indeed it would likely result in an amplified effect compared to the expected outcome. From now on, this analysis will be referred to with the acronym CC (car cost).

In the second approach, the 10% increase in car travel cost is achieved by imposing a tax on commodity production to each of the car mobility demands in the years after 2020. For each car mobility demand (*XS*, *S*, *M* and *L*) and each year, the tax level is calculated in each region as 10% of the shadow price obtained in the reference case. The demand shadow price, in the reference case (where demands are not elastic), represents the marginal supply cost associated to cover an additional car demand unit (Mpkm), and thus it can be interpreted as a proxy for car travel cost. However, also this method is approximate. Indeed, the shadow price is representative for the marginal technology, which is the most expensive technology deployed in the optimal solution. Theoretically, the price shock should hit the different car technologies differently by increasing every technology travel cost by 10% with respect to its original value in the reference case. From now on, this analysis will be referred to with the acronym CT (car tax).

The modal substitution obtained in the Price shock scenario for both analyses (CC and CT) are presented in Fig. 6.9 for the years 2040 and 2050:

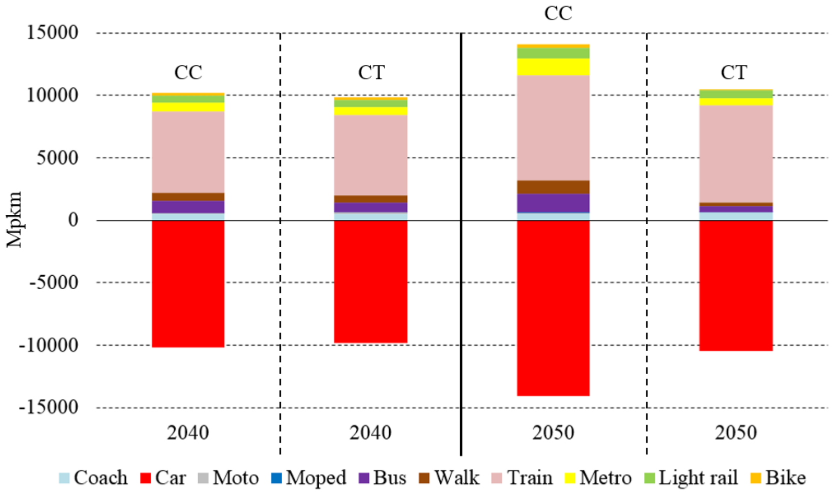


***Fig. 6.9**. Modal shift in 2040 and 2050 in the Price shock scenario in the Scandinavian countries obtained with TIMES-Nordic for both analyses: CC and CT.*

The modal shifts obtained in the two analyses (CC and CT) are very similar, with the only exception that the modal shift in the CC analysis increases in 2050 compared to 2040 and to the CT case. As mention before, decreasing car efficiency by 10% is a handy but rough way to emulate a 10% increase in fuel cost. Indeed, the higher fuel consumption compared to the reference case might result in a different marginal technology for fuel supply, and thus entails for a higher increase in fuel cost respect to the 10% assumed. This effect is most noticeable in 2050 because the car mobility demands defined in the reference case increase with increasing years, accounting in 2050 for a 30% higher level compared to 2010 in the whole Scandinavian region.

Besides this difference, both analyses show a shift from cars towards mainly train (and public transport in general) and non-motorised modes. In particular, car mobility demand decreases by around 4-5% in average in both analyses compared to the reference case, while train mobility demand increase by 18-19%.

As already mentioned in Section 6.2.1, transport elasticities measure the relative percentage change of a given transport quantity (or function), to a percentage change in factor affecting this quantity (or variable of the function). In this case, elasticities measure the relative percentage change in the demand for a specific mode with respect to a theoretical 10% increase in car travel cost. Eq. (6.5) is again used to calculate the implied elasticities in the Price shock scenario, though in this case the variations in shadow prices adopted for all modes are the ones of car demands as expressed in Eq. (6.6) (the superscript *ps* stands for Price shock scenario):

$$\sigma_{k,i}^{imp}(t) = \frac{\ln(\frac{DM_{k,i}^{ps}(t)}{DM_{k,i}^{0}(t)})}{\ln(\frac{p_{k,car}^{ps}(t)}{p_{k,car}^{0}(t)})} \tag{6.6}$$

Eq. (6.6) is applied to calculate $\sigma_{k,i}^{imp}(t)$ for each distance class *k*, each region and each year. Then, for each year, the weighted average $\bar{\sigma}_{i}^{imp}(t)$ is calculated across regions and distance classes using as weights the modal demands defined in the reference case.

First, in Table 6.6, the average implied "own-price" elasticities for cars obtained in the Price shock scenario for both analyses (CC and CT) are presented for 2040 and 2050 together with their averages across the two years and the weighted average substitution elasticity declared as input in the model σ_{car} (calculated previously in Table 6.3).

***Table 6.6**. Average implied car own-price elasticities in TIMES-Nordic in the Price shock scenario for the CC and the CT analyses presented for the years 2040 and 2050 together with their averages between the two years. The weighted average of the substitution elasticity assumed for car (σ_{car}) is also presented for comparison.*

Average $\boldsymbol{\sigma_{car}}$	$\boldsymbol{\bar{\sigma}_{car}^{imp,CC}}$ **(2040)**	$\boldsymbol{\bar{\sigma}_{car}^{imp,CC}}$ **(2050)**	**Average** $\boldsymbol{\bar{\sigma}_{car}^{imp,CC}}$	$\boldsymbol{\bar{\sigma}_{car}^{imp,CT}}$ **(2040)**	$\boldsymbol{\bar{\sigma}_{car}^{imp,CT}}$ **(2050)**	**Average** $\boldsymbol{\bar{\sigma}_{car}^{imp,CT}}$
-1.33	-1.37	-1.28	-1.33	-1.31	-1.06	-1.20

As it can be noted from Table 6.6, the average implied own-price elasticities obtained in both analyses, besides some fluctuations, are similar to the declared one (σ_{car}) (as presented in the previous section). In particular, the difference in shadow price between the elastic and the reference case for car is in average around 4% for both analyses, while the decrease in mobility demand is around 4-5%.

Concerning cross-price elasticities, they are calculated by applying Eq. (6.6) and are compared with transport literature. In particular, ref. [133] is taken as a benchmark for this comparison. Please note that ref. [133] is also the source used to identify the elasticity value used for car in Chapter 6. In this document, direct and cross elasticities are calculated for different modes under four main conditions: a 10% decrease in car or public transport cost and a 10% decrease in car or public transport travel time. For each of these conditions, direct (for car and public transport) and cross (for the other modes) elasticities are provided.

Since travel time is not modelled in TIMES-Nordic, the reference set of elasticities chosen as benchmark for this analysis is the 10% decrease in car cost. Moreover, the chosen elasticity set is representative for the purpose “commute” and is measured with respect to effect on “trips”. It is worth mentioning that elasticities vary largely with respect to the trip purpose and that the elasticity curve is usually asymmetric compared to parameter variations, meaning that the elasticity with respect to increasing the parameter would be different than the one obtained by decreasing the same parameter. In addition, ref. [133] provides semi-long-term elasticities instead of long-term, though, for the aim of this simple analysis, ref. [133] is assumed as a good landmark.

In Table 6.4, the average implied elasticities (own-price for car and cross-price for the other modes) calculated for both analyses (CC and CT) in the Price shock scenario are presented for the years 2040 and 2050 together with their average between the two years and are compared with the ones provided by [133]. It should be noted that for the category “Public” the average implied cross-price elasticity is calculated as weighed average across public transport modes using as weights the modal demands defined in the reference case.

Table 6.4. *Average implied own-price (for car) and cross-price (for the remaining modes) elasticities, calculated from the TIMES-Nordic Price shock scenario results for both analyses (CC and CT) in 2040 and 2050, and compared with the elasticities provided by* [133]*. *Average implied elasticities for each analysis are provided also as average between the two years (Avg.).*

Mode	**Elasticity***		**Mode**	$\bar{\sigma}_i^{imp,CC}(t)$		**Avg.** $\bar{\sigma}_i^{imp,CC}$	$\bar{\sigma}_i^{imp,CT}(t)$		**Avg.** $\bar{\sigma}_i^{imp,CT}$
				2040	**2050**		**2040**	**2050**	
Walk	0.25		**Walk**	2.10	2.28	2.19	1.89	0.78	1.33

Bike	0.24		**Bike**	1.50	1.54	1.52	1.50	1.60	1.55
Car driver	-0.16		**Car**	-1.37	-1.28	-1.33	-1.34	-1.07	-1.20
Car pass.	0.42								
Public	0.27		**Public**	4.82	4.07	4.44	4.79	3.87	4.33

The average implied own-price elasticities for car are much higher compared to the ones adopted from [133] for the category car driver. However, the elasticities for car were originally assumed from the “mileage” category and multiplied by a factor of three due to some misassumptions (as explained in Section 6.4.2). Indeed, the average implied own-price elasticities obtained for car are around three times higher than the assumed value (-0.426, [133] p. 96). For the other modes, the average implied cross-price elasticities reveal in general higher values compared to [133] especially for public transport modes. These higher values are partially due to the high substitution elasticities adopted for each aggregates (which were likely overestimated compared to reality as discussed in Section 6.4.2). However, the average implied elasticities calculated in this sub-section should be regarded as the percentage change in modal demand driven by a percentage increase in car shadow price. It is worth remembering again that, in general for a specific demand commodity, the shadow price calculated in the elastic case is not representative of the marginal supply cost to fulfil an additional unit of demand, while it is instead identified by a complex trade-off among quantities representing supply costs and consumer surplus due to the volume-preserving condition (as explained in the previous sub-section). Therefore, the deviations observed with respect to the assumed landmark result also from comparing two quantities embodying a different meaning. A more suitable approach to calculate implied own or cross-price elasticities starting from TIMES results, could be to adopt change in shadow price between the inelastic and the reference case. However, as already mentioned, it is not guaranteed that the marginal supply cost change obtained in this way can be assumed representative also for the elastic case. The large differences between optimization E4 models and transport models, for instance in the way travel costs are handled, make the comparison of elasticities an arduous task. Further research should focus on identifying a solid methodology to compare implied elasticities resulting from TIMES results with transport literature.

Besides this, adopting lower substitution elasticities would entail lower substitution rates among all modes and in turns to lower implied elasticities, though the elasticity values from the literature would probably still not met due to the major conceptual difference between the implied elasticities calculated in this sub-section with the ones provided in the literature. Moreover, each mode is characterised by the same substitution elasticity in each aggregate (σ_k), which obviously contributes to distorting the substitution trend compared to what is predicted by the cross-price elasticities in the literature. In light of this, further research should focus on the need to calibrate the elasticities used to reproduce the literature substitution trends in a similar way to what presented in this last analysis. For example, by introducing a known price shock that alters the travel cost of a specific mode and check for the substitution trend. This would be more controllable by introducing a characterization of substitution elasticities per mode (as already proposed in Section 6.4.1).

Besides the discrepancies between the obtained modal substitutions with those suggested by the transport literature, the methodology developed within this PhD thesis (elastic modal shift) has not the aim to substitute a transport model in any regards. On the contrary, it represents a modest first step towards the utilization of substitution elasticities in TIMES models to consider, in a simple way, dynamics affecting energy consumption and consequently emissions, which cannot be disregarded when tackling mitigation measures. To the author’s knowledge, at the time of writing and besides the papers included in this manuscript, there is no scientific literature yet on the utilization of substitution elasticities in TIMES models for any scope. Having said this, there is headroom for improvements and further research topics to address to enhance the modal shift emulation by using substitution elasticities.

7 OUTLOOK AND CONCLUSIONS

The final chapter of this thesis provides the outlook and conclusions of this PhD work. In particular, Section 7.1 presents an overview of the latest modelling updates characterising the TIMES-Nordic version available for download and discusses its capabilities within a scenario analysis perspective. Section 7.2 outlines weaknesses and suggestions for further research for TIMES-Nordic, while Section 7.3 presents the conclusions.

7.1 TIMES-NORDIC FOR SHIFT

During the end of the SHIFT project, TIMES-Nordic has been enriched by additional features compared to its previous version described in Chapter 4. These features are described in Section 7.1.1, while Section 7.1.2 discusses briefly how TIMES-Nordic can be used to support decision making in the Scandinavian region. It is worth saying that these improvements have been implemented through the joint efforts of the different scientists involved in the SHIFT project, to which the PhD student has also contributed. For this reason, only limited space has been reserved to their description in this PhD thesis.

7.1.1 ADDITIONAL FEATURES

Compared to the TIMES-Nordic version described in Chapter 4, new features have been included in order to fill ulterior gaps identified in Chapter 3. The new features concern mainly the inclusion of additional technology options. Following the order of recommendations outlined in Section 3.3, a simplified representation of shared cars and autonomous shared cars has been modelled. For each car type defined in TIMES-Nordic, a shared and an autonomous shared version has been included. These new versions differ from their conventional types in terms of technical features and costs. For instance, a higher mileage and a shorter life time are assumed due to the expected higher usage compared to conventional cars. In the case of autonomous shared cars, a higher investment cost has been assumed due to the additional electronics needed. The maximum penetration in the system of these types of car has been estimated based on different assumptions and studies (e.g. [144]). The user can adopt a high or low maximum penetration level respectively to emulate an optimistic or pessimistic adoption of these mobility options in his or her scenario analysis.

For the mode truck, diesel blending plug-in hybrid and hydrogen fuel cell trucks have been added. In addition, a simplified representation of electrified roads has been included as an accessory infrastructure option emulating the electrification of conventional roads. Only dedicated diesel blending plug-in hybrid and battery electric trucks can use the electrified roads defined. Moreover, the electrified roads expansion potential has been constrained based on the estimated capabilities of main arterial road freight corridors present in Scandinavia. One of the main source used to model electrified roads is [145].

Concerning additional ship types, dual fuelled natural gas, hydrogen and methanol ICE ships have been implemented for international freight maritime transport. However, other alternative technologies such as electric vessels, hydrogen fuel cell or ammonia ICE ships have not been modelled yet.

Regarding alternative fuel production chains, second-generation biofuels options have been enriched with additional biomass-to-liquid technologies that convert wood chips and wood waste material or wood pellets into biodiesel, ethanol or biokerosene. An additional process producing synthetic natural gas via gasification of wood chips and wood waste material has been added. Moreover, a “alcohol to jet fuel” process converting ethanol to kerosene has been included. The hydrogen production technology set has been enriched by solid oxide and proton exchange membrane cell electrolysers. Concerning electrofuels, additional production processes for kerosene and diesel have been modelled. In particular, the actual modelling architecture allows the model to produce electrofuels either by extracting directly the CO_2 from the air or using the CO_2 stored by CCS and BECCS technologies.

Lastly, for most of the transport modes, the possibility to include a reduction in future transport activity due to the adoption of different mitigation measures supporting the so-called Avoid pillar (see Section 2.2), has been implemented. The mitigation measures considered range from a better urban design to the optimization of the overall freight supply chain, their potentials have been estimated based on [144]. The user can activate or deactivate this feature when running the model.

Information on how to download TIMES-Nordic and get access to all input data and assumptions on which the new features and the rest of the model are based are provided in the next section.

7.1.2 SUPPORTING SCANDINAVIAN DEBATE

TIMES-Nordic can be applied to investigate the possible evolution of the entire Scandinavian (and possibly in the future, Nordic) energy system under different assumptions. Socio-economic analyses aimed at achieving specific environmental goals, such as those outlined under the Paris agreement, can be investigated. Specific technological strategies can be tested in terms of their feasibility and in light of National resources availability, or challenged by restrictive conditions, for instance, by limiting the import of energy carriers (e.g. biofuels). The effectiveness of dedicated sector policies and their effect on the overall energy system can be explored comprehensively due to the full-sector nature of TIMES-Nordic. Moreover, thanks to the implementation of elastic modal shift, transport policies can be investigated in terms of their impact on modal competition, thus their effectiveness in stimulating a shift from carbon-intense modes towards less carbon-intense ones can be tested endogenously.

At the actual stage, the inclusion of national policies, such as energy taxes or transport fiscal frameworks, is under implementation and soon will be available.

In order to make TIMES-Nordic results publicly available within the SHIT project, an interactive web-interface has been developed (http://shift.tokni.com), where most recent scenario analyses can be consulted. The webpage includes also descriptive background material such as main assumptions and scenarios description. The users can compare two scenarios at a time while being able to activate/deactivate few ground assumptions identified as pivotal in the presented scenarios to check upon their impact on the overall energy system. Moreover, results are available for single countries as well as for the entire Scandinavian region. The main reason to develop such a tool is to disseminate scientific results and to promote a public debate on the topic. The greatest hope is to involve relevant stakeholders in a public discussion on a common Scandinavian decarbonisation strategy and to support policymakers in identifying effective measures to reach the environmental goals set in the Scandinavian region.

TIMES-Nordic can be downloaded by following the instructions available at: http://shift.tokni.com.

7.2 FURTHER RESEARCH

In Chapter 3, modelling improvements and recommendations for analyses addressing the decarbonisation of the Nordic transport sector have been presented. Part of these recommendations have been tackled along this PhD project and within the SHIFT project through the development of TIMES-Nordic and the novel methodology emulating transport modal shift. As mentioned in Section 4.3, filling the identified gaps by developing an open-source model represents a relevant scientific contribution to the Scandinavian energy modelling community, because it enables fellow researchers to enrich the Scandinavian analysis with additional scenarios not hindered by the shortcomings identified in the previous literature (on which are based the gaps identification in Chapter 3). However, a few recommendations still need to be addressed.

Concerning the methodology developed to model elastic transport modal shift (Chapter 5) and its application (Chapter 6), weaknesses/limitations and dedicated suggestions for further research have been already outlined at the end of Chapter 6. However, it is worth mentioning that the methodology could be applied to describe other phenomena than transport modal shift, where demand substitutions take place with similar dynamics. Additionally, TIMES models offer different variants for substitution elasticities to the volume-preserving assumption adopted in this PhD [123], and these can be used for best describing case-specific phenomena. Further research could investigate the adoption of substitution elasticities to describe similar mechanisms in other sectors.

Regarding the architecture of TIMES-Nordic, at the actual stage only Denmark, Norway and Sweden are modelled, this makes it a Scandinavian model. The inclusion of Iceland and Finland is fundamental to enable energy scenario analyses for the whole Nordic region, which would be a desirable achievement in light of the motivation presented in Chapter 1. Regarding the inclusion of breakthrough transport technologies, electric ferries and additional ship types, such as hydrogen fuel cell and ammonia ICE vessels, represent a desirable improvement. The characterization of shared cars and autonomous shared cars could be improved. For instance, their occupancy factors could be differentiated compared to conventional cars by assuming higher values. The same applies to the efficiency of autonomous shared cars. Indeed, the adoption of intelligent transport systems on board could lead to a more efficient use of the engine. In addition, even though the international transport sector has been modelled in TIMES-Nordic, its characterization is affected by a larger degree of uncertainty compared to the rest of the transport sector due to the limited amount of available data (as briefly mentioned in Appendix B). Further research should focus on achieving a more accurate description for this sector, for instance by relying on more solid dataset compared to the one used by the author.

Moreover, additional GHG emissions (besides CO_2) and non-energy related emissions could be modelled in order to provide a more comprehensive overview of the potential contribution of specific technologies or fuel chains to global warming. In addition, other relevant pollutants such as particulate, NOx and SO_2 could be included in order to monitor the effects of specific technologies on air quality, an important issue, especially in cities. An additional recommendation for further research relates to enhancing the representation of the spatial dimension, for instance, by differentiating between urban and non-urban areas (as already mentioned in Section 6.4.1). As outlined in Section 2.2, cities will most likely play an increasing important role in terms of transport activities and energy use. However, cities are often more ambitious than their national governments in terms of environmental goals, as witnessed by initiatives such as the C40 Cities Climate Leadership Group (C40) [146]. This is particularly true for the Nordic capitals, which are already innovation hubs of sustainable mobility. Energy system models could support the investigation and analysis of further urban mitigation actions by depicting such innovation momentum in their architecture.

Besides the spatial dimension, the modelling architecture of the transport sector in TIMES-Nordic could be improved in terms of the temporal resolution. Indeed, all the mobility demands are defined annually and they are not characterised per time slice. This could lead to an overestimation of the feasibility of the obtained solution by simplifying energy consumption patterns. Enhancing the temporal resolution could be quite relevant, for instance, in such cases where a strong electrification takes place (such as in many of the reviewed scenarios). Last but not least, despite the weaknesses and possible improvements outlined above, TIMES-Nordic is already capable to support Scandinavian integrated energy and transport scenario analysis as briefly illustrated in the previous section. Given its open-source nature, it is desirable that energy analysts and modellers will adopt TIMES-Nordic as a tool for their future research and hopefully they will contribute to its further development. Finally, in Table 7.1, strengths/novelty and weaknesses/limitations of the three main subjects discussed in Section 6.4 and 7.2 are summarized together with the identified recommendations for further research:

Table 7.1. *Strengths/novelty, weaknesses/limitations and relative suggestions for further research are summarised for the three main research topics discussed in Chapter 6 and 7. Dashed lines indicate that the suggested improvement relates specifically to the weakness/limitation presented within the same row, continue vertical lines indicate independent topics between the two fields.*

	Strengths/novelty	**Weaknesses/limitations**	**Further research and improvements**
Elastic modal shift (methodology)	Introduce modal competition in E4 optimization E4 models. For passenger, it emulates transport behaviour. For freight, it emulates market arrangements resulting from variations in modal transport costs. It paves the way for a broader set of policy analyses	Severe simplification of the described phenomenon: modal substitution ignores several level of service parameters such as modal travel time/speed	Include travel time budged concept and modal speed
	Compact modelling set-up	Aggregated substitution elasticities σ_k, no characterization by transport mode	Define substitution elasticities per mode ($\sigma_{k,i}$) in each aggregate k
	Low data requirement		
	Low impact on computational time	Aggregated transport spatial dimension	Include urban and non-urban characterization
		Possible unrealism in modal substitution	Calibration of the adopted elasticities
TIMES-Nordic analysis	First application of elastic modal shift adopting transport elasticities from the literature	Misassumptions and approximations in the elasticity values adopted	Identify most recent own-price elasticities for the studied countries
	Identification of the transport elasticity type that best suits the modelling environment adopted	Transport infrastructure not modelled	Model transport infrastructure for each mode
		Lack of alternative technologies for some modes e.g. freight ships and trucks	Include an exhaustive technology database for all modes participating to modal shift
	Modal shift levels comparable to results obtained by a few recent study addressing the same topic	Possible overestimation of the modal shift levels	Estimate modal shift levels with higher CO_2 tax levels
			Characterise freight sub-sector (modal technologies and demands) per good transported

TIMES-Nordic structure	Single-country description aggregated by power regions	Only Denmark, Norway and Sweden are included	Model Finland and Iceland
	Full energy system description	Approximate description of the international transport sector	Improve international transport description for shipping and aviation
	Full transport sector description	Lack of a complete set of ships technologies	Include additional ship technologies
	Detailed transport technology set	Only energy-related CO_2 emissions included	Model additional GHG emissions and pollutants
	Rich biofuel and electrofuels production technologies set	Transport sector temporal resolution characterised only at an annual level	Enhance the transport sector temporal description
	Simple description of electrified roads, shared and autonomous shared cars	Shared and autonomous shared modelled in a simplistic way	Improve the representation of these technologies/phenomena
	Detailed CCS and BECCS technologies set for the industry and power and heat sectors	Urban and non-urban characterization not captured	Enhance the spatial characterization
	Soon open-source		

7.3 CONCLUSIONS

This PhD thesis contributes to the scientific progress in the field of energy system analysis and modelling, specifically tackling the decarbonisation of the Scandinavian transport sector. The “burning platform” represented by the actual unsustainability of the transport sector and the upcoming global challenges for its low-carbon transition were introduced and possible mitigation measures presented (Section 2.2, based on Paper **I**).

The actual state-of-the-art of studies applying energy system analysis for integrated energy and transport scenarios for the Nordic region was investigated by carrying out a systematic literature review (Chapter 3, based on Paper **II**). The review highlighted research gaps and potential modelling improvements in light of recent transport literature and partly considering the challenges and potential mitigation strategies outlined in Section 2.2.

Part of the identified gaps were tackled along the PhD studies through two main scientific contributions. The first contribution addresses an important weakness of BU optimization E4 models: the poor representation of transport modal competition. An original methodology enabling transport modal shift through the application of substitution elasticities was developed to tackle this gap (Chapter 5, based on Paper **III**). For the passenger sub-sector, this represents an attempt to enhance the weak capability of BU optimization E4 models to depict transport behavioural dynamics in their modelling framework. The development of TIMES-Nordic, which was one of the main tasks of this PhD project, represents the second contribution to tackle the gaps identified in Chapter 3. Indeed, its structure was largely designed to fill most of the modelling limitations identified in the reviewed literature.

The novel methodology, enabling endogenous modal shift, was developed as a tailored approach for large multi-regional models such as TIMES-Nordic. Indeed, the compactness and lower data requirement compared to alternative methods (see Section 3.3.1, based on Paper **III**) facilitate its implementation in large models. However, the simplicity of this approach results into a severe simplification of the described phenomenon. The novel methodology was firstly tested (Paper **III**) and then applied for a real case study using TIMES-Nordic (Chapter 6, based on Paper **IV**). Direct long-term own-price elasticities were identified as the most suitable quantities available from transport literature to be applied in the modelling context assumed. Moreover, the main modelling implications, such as the interactions with other constraints defined (e.g. travel patterns), were discussed in light of the TIMES-Nordic structure. In particular, the novel methodology was applied to investigate the role of modal shift in decarbonising the future Scandinavian transport sector under an increasing CO_2 tax. Transport modal shift, towards the more efficient and less carbon-intense modes (e.g. rail), resulted a cost-effective measure to reduce cumulative CO_2 emissions. However, due to a number of modelling limitations and data assumptions/approximations the modal shift levels obtained seem to be overestimated (Section 6.4.2). For instance, some assumptions, adopted to align the modal elasticities assumed from transport literature to the type suggested to be used as input, led to an overestimation of the modal elasticities adopted (e.g. for car). This is an important point, since the model is usually quite sensitive to the elasticity values declared, as shown in dedicated sensitivity analyses in Paper **III** and **IV**. Potential users of the developed methodology should pay particular attention when selecting such inputs. Moreover, the absence of transport infrastructure description in TIMES-Nordic may also have contributed to overestimating the modal shift levels due to the possible additional costs related to infrastructure expansion not captured by the model, especially for these modes with large demand increases (such as rail). A set of suggestions for further research aiming at improving the quality of the results has been identified. For example, besides the inclusion of transport infrastructure for all modes described, a higher disaggregation of the spatial dimension, e.g. differentiating between urban and non-urban areas, and the inclusion of a travel time budget concept could improve the validity of the results. Moreover, a more comprehensive description of technologies across modes respect to the adopted one is recommended to guarantee fair competition. Besides, the possibility to declare a specific modal elasticity in each demand aggregate, which is possible with the elastic demand formulations in TIMES models, is an easily implementable improvement, which would enhance modal representation and would avoid unnecessary elasticity aggregation steps. Lastly, another possible improvement, which has been identified by analysing the implied elasticities calculated (a posteriori) from TIMES-Nordic results (Section 6.5.2.2), is to calibrate the assumed elasticities values in order to reproduce transport elasticities available in the scientific literature before using them for scenario analysis. However, a major challenge is represented by the large differences between the modelling framework characterising BU optimization E4 models and transport models, e.g. in the way transport costs are handled.

Despite the limitations and approximations discussed (summarised in Table 7.1), when comparing the obtained modal shift levels with other studies addressing the same topic, similar results are revealed (Section 6.4.1). However, a systematic validation is impossible due to the scarcity of studies investigating the same topic. For this reason, a simple MNL model has been developed and applied to calculate modal shares variations for the same case study investigated to be compared with the modal shift obtained with TIMES-Nordic (Section 6.5.1). The MNL analysis, carried out only for the Danish inland passenger sector, reveals much lower modal shift levels (under the assumed CO_2 tax), representing a further evidence supporting the modal shift overestimation. Besides the modal shift magnitudes, the substitution trends are qualitatively similar to the ones obtained with TIMES-Nordic. The MNL analysis suggests that the assumed CO_2 tax levels are ineffective to stimulate a significant modal shift across the whole time horizon. Therefore, another suggestion for further research is to investigate modal shift under higher CO_2 tax levels compared to the ones assumed within this study.

Nevertheless, the developed methodology enables more comprehensive analyses by incorporating, beside a detailed technological dimension, a simplified representation of transport behavioural dynamics in a unique modelling framework. Moreover, although behaviour only plays a limited role in freight transportation compared to passengers, modal shift is also relevant within the former sector. Indeed, the European Commission included freight modal shift among the ten main goals to be pursued by 2030 in its White Paper [147]. The novel methodology presented in this PhD thesis enables endogenous modal shift for both the passenger and freight sub-sectors, representing further progress compared to previous attempts in BU optimization E4 models, which focus mainly on passengers (see Section 3.3.1, based on Paper **III**).

Including modal competition in BU optimization E4 models has a broad scientific impact on integrated energy and transport scenarios analysis, it paves the way for a wider range of applications aimed at investigating how to reach a low-carbon transport sector compared to traditional approaches. The so-called Shift pillar, at the base of the decarbonisation strategy proposed by IEA (Section 2.2), can be investigated directly in a unique modelling framework. For instance, the developed methodology can be applied to test the effectiveness of dedicated energy and transport policies aiming at supporting modal shift (e.g. “Push” and “Pull” instruments) for both the passenger and freight sub-sectors. Besides, alternative taxation schemes and mitigation measures or targets could be investigated in terms of their potential effect on modal shares. However, the transport policy instruments investigation is limited to such measures influencing dimensions/features captured by the adopted modelling framework.

Regarding TIMES-Nordic, several of its features were moulded based on recommendations outlined in Chapter 3. Besides including elastic modal shift, the model was enriched by breakthrough energy and transport technologies and innovative fuel chains. The energy system of each country was modelled separately, allowing the investigation of sustainable pathways for the whole Scandinavian region while enabling the identification of specific national decarbonisation strategies. All sectors composing the national energy systems were included, this allows to explore resource competition and technological synergies across sectors when fulfilling common environmental targets. Lastly, all transport sub-sectors (including international aviation and navigation) were included in TIMES-Nordic to provide a complete outlook when addressing emission reduction strategies. Besides the modelling strengths, TIMES-Nordic presents also some shortcomings and headroom for improvements (see Table 7.1). For instance, the inclusion of additional GHG emissions (besides CO_2) together with other transport pollutants (e.g. NO_X and SO_2) is recommended to provide a wider environmental assessment of the analysed scenarios. Moreover, the transport mobility demands are characterised only at an annual level, this could undermine the feasibility of the obtained results due to the oversimplification of energy consumption patterns. Enhancing such temporal resolution would lead to more solid results especially in such cases where a strong electrification takes place.

Lastly, TIMES-Nordic represents a relevant scientific contribution to the Scandinavian energy modelling community because it can support further integrated energy and transport scenario analyses not hindered by the shortcomings identified in the previous literature. This is even more relevant considering that TIMES-Nordic will soon be open-source and thus available to support fellow researchers in enriching the Scandinavian analyses for a low-carbon transition of the energy system.

Concluding, this PhD thesis provides tools (publicly available) and methodologies that can support fellow researchers and modellers interested in the decarbonisation of the Scandinavian (and possibly Nordic) transport sector, together with a set of suggestions for further research.

Finally, even though the recommendations presented in Chapter 3 were outlined to enhance the integrated energy and transport modelling for the Nordic region, which brought to the development of TIMES-Nordic, most of them are generally valid beyond the Nordic case. Moreover, the adoption of substitution elasticities to emulate transport modal competition in BU optimization E4 models can be applied in any TIMES model regardless its geographical scope, and can be potentially used to model similar dynamics in other sectors.

REFERENCES

[1] International Energy Agency. Energy Technology Perspectives 2016: Towards Sustainable Energy Systems. Paris, France: 2016.

[2] Sims R, Schaeffer R, Creutzig F, Cruz-Núñez X, D'Agosto M, Dimitriu D, et al. Transport Climate Change 2014: Mitigation of Climate Change. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, editors. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press; 2014.

[3] International Energy Agency. Energy Technology Perspectives 2017: Catalysing Energy Technology Transformations. Paris, France: 2017.

[4] International Energy Agency. Nordic EV Outlook 2018. Paris, France: 2018.

[5] International Energy Agency. The Future of Trucks - Implications for energy and the environment. Paris, France: 2017.

[6] Stocker TF, Qin D, Plattner G-K, Tignor M, Allen AK, Boschung J, et al. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA: 2013.

[7] International Energy Agency. Energy Technology Perspectives 2015: Mobilising Innovation to Accelerate Climate Action. Paris, France: 2015.

[8] International Energy Agency. Transport, Energy and CO_2. Paris, France: 2009.

[9] International Energy Agency. Energy Technology Perspectives 2014: Harnessing Electricity's Potential. Paris, France: 2014.

[10] United Nations Framework Convention on Climate Change. The Paris Agreement. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (accessed May 10, 2019).

[11] International Transport Forum. Transport CO_2 and Paris Agreement Reviewing the Impact of Nationally Determined Contributions. Paris, France: 2018.

[12] International Energy Agency. World Energy Outlook 2018. Paris, France: 2018.

[13] International Energy Agency, Nordic Energy Research. Nordic Energy Technology Perspectives 2016. Paris, France. Oslo, Norway: 2016. doi:10.1787/9789264257665-en.

[14] Nordic Council of Ministers (Norden). Energy and Transport. Copenhagen, Denmark: 2014. doi:10.6027/TN2014-537.

[15] Nordic Action Group on Climate and Energy. Nordic Transport Ways. Stockholm, Sweden: 2015.

[16] Lopion P, Markewitz P, Robinius M, Stolten D. A review of current challenges and trends in energy systems modeling. Renew Sustain Energy Rev 2018;96:156–66. doi:10.1016/j.rser.2018.07.045.

[17] Salvucci R, Petrović S, Karlsson K, Wråke M, Uteng TP, Balyk O. Energy Scenario Analysis for the Nordic Transport Sector: A Critical Review. Energies 2019;12:2232. doi:10.3390/en12122232.

[18] Münster M, Morthorst PE, Larsen H V., Bregnbæk L, Werling J, Lindboe HH, et al. The role of district heating in the future Danish energy system. Energy 2012;48:47–55. doi:10.1016/j.energy.2012.06.011.

[19] Petrović SN, Karlsson KB. Residential heat pumps in the future Danish energy system. Energy 2016;114:787–97. doi:10.1016/j.energy.2016.08.007.

[20] Tattini J, Gargiulo M, Karlsson K. Reaching carbon neutral transport sector in Denmark – Evidence from the incorporation of modal shift into the TIMES energy system modeling framework. Energy Policy 2018;113:571–83. doi:10.1016/j.enpol.2017.11.013.

[21] Börjesson M, Ahlgren EO, Lundmark R, Athanassiadis D. Biofuel futures in road transport – A modeling analysis for Sweden. Transp Res Part D Transp Environ 2014;32:239–52. doi:10.1016/j.trd.2014.08.002.

[22] Loulou R, Goldstein G, Kanudia A, Lehtilä A, Remme U. Documentation for the TIMES Model - Part I: TIMES concepts and theory. Energy Systems Technology Analysis Programme (ETSAP); 2016.

[23] International Energy Agency. ETSAP - Energy Technology Systems Analysis Programme. https://iea-etsap.org/ (accessed November 20, 2018).

[24] Lind A, Espegren K. The use of energy system models for analysing the transition to low-carbon cities – The case of Oslo. Energy Strateg Rev 2017;15:44–56. doi:10.1016/j.esr.2017.01.001.

[25] Føyn THY, Karlsson K, Balyk O, Grohnheit PE. A global renewable energy system: A modelling exercise in ETSAP/TIAM. Appl Energy 2011;88:526–34. doi:10.1016/j.apenergy.2010.05.003.

[26] Chiodi A, Gargiulo M, Rogan F, Deane JP, Lavigne D, Rout UK, et al. Modelling the impacts of challenging 2050 European climate mitigation targets on Ireland's energy system. Energy Policy 2013;53:169–89. doi:10.1016/j.enpol.2012.10.045.

[27] Yang C, Yeh S, Zakerinia S, Ramea K, McCollum D. Achieving California's 80% greenhouse gas reduction target in 2050: Technology, policy and scenario analysis using CA-TIMES energy economic systems model. Energy Policy 2015;77:118–30. doi:10.1016/j.enpol.2014.12.006.

[28] McCollum D, Yang C, Yeh S, Ogden J. Deep greenhouse gas reduction scenarios for California – Strategic implications from the CA-TIMES energy-economic systems model. Energy Strateg Rev 2012;1:19–32. doi:10.1016/j.esr.2011.12.003.

[29] Bahn O, Marcy M, Vaillancourt K, Waaub J-P. Electrification of the Canadian road transportation sector: A 2050 outlook with TIMES-Canada. Energy Policy 2013;62:593–606. doi:10.1016/j.enpol.2013.07.023.

[30] Zhang H, Chen W, Huang W. TIMES modelling of transport sector in China and USA: Comparisons from a decarbonization perspective. Appl Energy 2016;162:1505–14. doi:10.1016/j.apenergy.2015.08.124.

[31] Karlsson KB, Petrović SN, Næraa R. Heat supply planning for the ecological housing community Munksøgård. Energy 2016;115:1733–47. doi:10.1016/j.energy.2016.08.064.

[32] Rosenberg E, Lind A, Espegren KA. The impact of future energy demand on renewable energy production – Case of Norway. Energy 2013;61:419–31. doi:10.1016/j.energy.2013.08.044.

[33] Krook Riekkola A, Ahlgren EO, Söderholm P. Ancillary benefits of climate policy in a small open economy: The case of Sweden. Energy Policy 2011;39:4985–98. doi:10.1016/j.enpol.2011.06.015.

[34] International Energy Agency. CO_2 Emissions Statistics. https://www.iea.org/statistics/co2emissions/ (accessed May 10, 2019).

[35] International Energy Agency, International Council on Clean Transportation. Fuel Economy in Major Car Markets: Technology and Policy Drivers 2005-2017. Paris, France: 2019.

[36] International Energy Agency. Digitalization & Energy. Paris, France: 2017.

[37] International Energy Agency. The Future of Rail - Opportunities for energy and the environment. Paris, France: 2019.

[38] International Transport Forum. ITF Transport Outlook 2017. Paris, France: 2017. doi:10.1787/9789282108000-en.

[39] International Energy Agency. Global EV Outlook 2019 - Scaling-up the transition to electric mobility. Paris, France: 2019.

[40] International Energy Agency. Renewables 2018 - Analysis and Forecasts to 2023. Paris, France: 2018.

[41] International Civil Aviation Organisation. Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) 2019. https://www.icao.int/environmental-protection/CORSIA/Pages/default.aspx (accessed May 10, 2019).

[42] International Maritime Organization. UN body adopts climate change strategy for shipping. http://www.imo.org/en/MediaCentre/PressBriefings/Pages/06GHGinitialstrategy.aspx (accessed May 10, 2019).

[43] International Maritime Organization. Energy Efficiency Measures. http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Technical-and-Operational-Measures.aspx (accessed May 10, 2019).

[44] International Maritime Organization. Sulphur 2020 – cutting sulphur oxide emissions. http://www.imo.org/en/MediaCentre/HotTopics/Pages/Sulphur-2020.aspx (accessed May 10, 2019).

[45] Web of Science. https://www.webofknowledge.com (accessed March 13, 2019).

[46] DTU Findit. https://findit.dtu.dk (accessed March 13, 2019).

[47] Scopus. https://www.scopus.com (accessed March 13, 2019).

[48] Liu Z, Wu Q, Nielsen A, Wang Y. Day-Ahead Energy Planning with 100% Electric Vehicle Penetration in the Nordic Region by 2050. Energies 2014;7:1733–49. doi:10.3390/en7031733.

[49] Graabak I, Wu Q, Warland L, Liu Z. Optimal planning of the Nordic transmission system with 100% electric vehicle penetration of passenger cars by 2050. Energy 2016;107:648–60. doi:10.1016/j.energy.2016.04.060.

[50] Juul N, Meibom P. Road transport and power system scenarios for Northern Europe in 2030. Appl Energy 2012;92:573–82. doi:10.1016/j.apenergy.2011.11.074.

[51] Taljegard M, Göransson L, Odenberger M, Johnsson F. Impacts of electric vehicles on the electricity generation portfolio – A Scandinavian-German case study. Appl Energy 2019;235:1637–50. doi:10.1016/j.apenergy.2018.10.133.

[52] Bright RM, Strømman AH. Fuel-Mix, Fuel Efficiency, and Transport Demand Affect Prospects for Biofuels in Northern Europe. Environ Sci Technol 2010;44:2261–9. doi:10.1021/es903135c.

[53] Meibom P, Karlsson K. Role of hydrogen in future North European power system in 2060. Int J Hydrogen Energy 2010;35:1853–63. doi:10.1016/j.ijhydene.2009.12.161.

[54] Sørensen B. A renewable energy and hydrogen scenario for northern Europe. Int J Energy Res 2008;32:471–500. doi:10.1002/er.1376.

[55] Koljonen T, Pursiheimo E, Gether K, Jøregensen K. System Analysis and Assessment of Technological Alternatives for Nordic H2 Energy Foresight. Risø National Laboratory: Roskilde, Denmark: 2004.

[56] Seljom P, Rosenberg E. A Scandinavian Transition Towards a Carbon-Neutral Energy System. In: Limiting Global Warming toWell Below 2˚C: Energy System Modelling and Policy Development. Giannakidis G, Karlsson K, Labriet M, Gallachóir B, editors. Lect. Notes Energy, vol. 64, Springer; Berlin, Germany, 2018; Volume 64, pp. 105–21. doi:10.1007/978-3-319-74424-7_7.

[57] Pursiheimo E, Holttinen H, Koljonen T. Path toward 100% renewable energy future and feasibility of power-to-gas technology in Nordic countries. IET Renew Power Gener 2017;11:1695–706. doi:10.1049/iet-rpg.2017.0021.

[58] International Energy Agency. Modelling of the transport sector in the Mobility Model 2017. https://www.iea.org/etp/etpmodel/transport/ (accessed July 12, 2017).

[59] Daly HE, Ramea K, Chiodi A, Yeh S, Gargiulo M, Gallachóir BÓ. Incorporating travel behaviour and travel time into TIMES energy system models. Appl Energy 2014;135:429–39. doi:10.1016/j.apenergy.2014.08.051.

[60] Pye S, Daly H. Modelling sustainable urban travel in a whole systems energy model. Appl Energy 2015;159:97–107. doi:10.1016/j.apenergy.2015.08.127.

[61] Tattini J, Ramea K, Gargiulo M, Yang C, Mulholland E, Yeh S, et al. Improving the representation of modal choice into bottom-up optimization energy system models – The MoCho-TIMES model. Appl Energy 2018;212:265–82. doi:10.1016/j.apenergy.2017.12.050.

[62] Cayla J-M, Maïzi N. Integrating household behavior and heterogeneity into the TIMES-Households model. Appl Energy 2015;139:56–67. doi:10.1016/j.apenergy.2014.11.015.

[63] Salvucci R, Tattini J, Gargiulo M, Lehtilä A, Karlsson K. Modelling transport modal shift in TIMES models through elasticities of substitution. Appl Energy 2018;232:740–51. doi:10.1016/j.apenergy.2018.09.083.

[64] Connolly D. Economic viability of electric roads compared to oil and batteries for all forms of road transport. Energy Strateg Rev 2017;18:235–49. doi:10.1016/j.esr.2017.09.005.

[65] Ahjum F, Merven B, Stone A, Caetano T. Road transport vehicles in South Africa towards 2050: Factors influencing technology choice and implications for fuel supply. J Energy South Africa 2018;29. doi:10.17159/2413-3051/2018/v29i3a5596.

[66] Ishimoto Y, Kurosawa A, Sasakura M, Sakata K. Significance of CO_2 -free hydrogen globally and for Japan using a long-term global energy system analysis. Int J Hydrogen Energy 2017;42:13357–67. doi:10.1016/j.ijhydene.2017.02.058.

[67] Oshiro K, Masui T. Diffusion of low emission vehicles and their impact on CO_2 emission reduction in Japan. Energy Policy 2015;81:215–25. doi:10.1016/j.enpol.2014.09.010.

[68] Kawakami Y, Komiyama R, Fujii Y. Penetration of Electric Vehicles toward 2050: Analysis Utilizing an Energy System Model Incorporating High-Temporal-Resolution Power Generation Sector. IFAC-PapersOnLine 2018;51:598–603. doi:10.1016/j.ifacol.2018.11.769.

[69] Teir S, Tsupari E, Arasto A, Koljonen T, Kärki J, Lehtilä A, et al. Prospects for application of CCS in Finland. Energy Procedia 2011;4:6174–81. doi:10.1016/j.egypro.2011.02.628.

[70] Victor N, Nichols C, Zelek C. The U.S. power sector decarbonization: Investigating technology options with MARKAL nine-region model. Energy Econ 2018;73:410–25. doi:10.1016/j.eneco.2018.03.021.

[71] Huang W, Chen W, Anandarajah G. The role of technology diffusion in a decarbonizing world to limit global warming to well below 2 °C: An assessment with application of Global TIMES model. Appl Energy

2017;208:291–301. doi:10.1016/j.apenergy.2017.10.040.

[72] Simoes S, Nijs W, Ruiz P, Sgobbi A, Thiel C. Comparing policy routes for low-carbon power technology deployment in EU – an energy system analysis. Energy Policy 2017;101:353–65. doi:10.1016/j.enpol.2016.10.006.

[73] Blanco H, Nijs W, Ruf J, Faaij A. Potential for hydrogen and Power-to-Liquid in a low-carbon EU energy system using cost optimization. Appl Energy 2018;232:617–39. doi:10.1016/j.apenergy.2018.09.216.

[74] Schäfer A. Introducing Behavioral Change in Transportation into Energy / Economy / Environment Models. Policy research working paper no. WPS 6234. Washington, DC: World Bank; 2012.

[75] Venturini G, Tattini J, Mulholland E, Ó Gallachóir B. Improvements in the representation of behaviour in integrated energy and transport models. Int J Sust Transp 2018. doi:10.1080/15568318.2018.1466220.

[76] Baptista P, Melo S, Rolim C. Energy, Environmental and Mobility Impacts of Car-sharing Systems. Empirical Results from Lisbon, Portugal. Procedia - Soc Behav Sci 2014;111:28–37. doi:10.1016/j.sbspro.2014.01.035.

[77] E3MLab/ICCS at National Technical University of Athens. PRIMES-TREMOVE Transport Model, Detailed model description. Athens, Greece: 2014.

[78] Girod B, van Vuuren DP, Deetman S. Global travel within the 2°C climate target. Energy Policy 2012;45:152–66. doi:10.1016/j.enpol.2012.02.008.

[79] McCollum DL, Wilson C, Pettifor H, Ramea K, Krey V, Riahi K, et al. Improving the behavioral realism of global integrated assessment models: An application to consumers' vehicle choices. Transp Res Part D Transp Environ 2017;55:322–42. doi:10.1016/j.trd.2016.04.003.

[80] Brand C, Tran M, Anable J. The UK transport carbon model: An integrated life cycle approach to explore low carbon futures. Energy Policy 2012;41:107–24. doi:10.1016/j.enpol.2010.08.019.

[81] National Transport Authority. Regional Modelling System – Full demand model specification report. Dublin, Ireland: 2017.

[82] Cambridge Systematics. California Statewide Travel Demand Model, Version 2.0 - Model Overview - Final Report. Oakland, CA, USA: 2014.

[83] Sillaparcharn P. National Transport Demand Modelling - General Approach and Application to Thailand. Leeds, UK: 2007.

[84] Karplus VJ, Paltsev S, Babiker M, Reilly JM. Applying engineering and fleet detail to represent passenger vehicle transport in a computable general equilibrium model. Econ Model 2013;30:295–305. doi:10.1016/j.econmod.2012.08.019.

[85] Pietzcker R, Moll R, Bauer N, Luderer G. Vehicle technologies and shifts in modal split as mitigation options towards a 2°C climate target. Int. Soc. Ecol. Econ. 11th Bienn. Conf., Oldernburg: 2010.

[86] Horne M, Jaccard M, Tiedemann K. Improving behavioral realism in hybrid energy-economy models using discrete choice studies of personal transportation decisions. Energy Econ 2005;27:59–77. doi:10.1016/j.eneco.2004.11.003.

[87] Iacobucci R, McLellan B, Tezuka T. The Synergies of Shared Autonomous Electric Vehicles with Renewable Energy in a Virtual Power Plant and Microgrid. Energies 2018;11:2016. doi:10.3390/en11082016.

[88] Sovacool BK. Contestation, contingency, and justice in the Nordic low-carbon energy transition. Energy Policy 2017;102:569–82. doi:10.1016/j.enpol.2016.12.045.

[89] Gagatsi E, Estrup T, Halatsis A. Exploring the Potentials of Electrical Waterborne Transport in Europe: The E-ferry Concept. Transp Res Procedia 2016;14:1571–80. doi:10.1016/j.trpro.2016.05.122.

[90] Martinsen K, Torvanger A. Control mechanisms for Nordic ship emissions. TemaNord, Nordic Council of Ministers: Copenhagen, Denmark: 2013. doi:10.6027/TN2013-518.

[91] Rootzén J, Johnsson F. CO_2 emissions abatement in the Nordic carbon-intensive industry – An end-game in sight? Energy 2015;80:715–30. doi:10.1016/j.energy.2014.12.029.

[92] Krook-Riekkola A, Sandberg E. Net-Zero CO_2-Emission Pathways for Sweden by Cost-Efficient Use of Forestry Residues. In: Limiting Global Warming to Well Below 2˚C: Energy System Modelling and Policy Development; Giannakidis G, Karlsson K, Labriet M, Ó Gallachóir B, editors; Lecture Notes in Energy; Springer: Berlin, Germany, 2018; Volume 64, pp. 123–36. doi:10.1007/978-3-319-74424-7_8.

[93] Rydén M, Lyngfelt A, Langørgen Ø, Larring Y, Brink A, Teir S, et al. Negative CO_2 Emissions with Chemical-Looping Combustion of Biomass – A Nordic Energy Research Flagship Project. Energy Procedia 2017;114:6074–82. doi:10.1016/j.egypro.2017.03.1744.

[94] Anthonsen KL, Aagaard P, Bergmo PES, Erlström M, Fareide JI, Gislason SR, et al. CO_2 Storage Potential in the Nordic Region. Energy Procedia 2013;37:5080–92. doi:10.1016/j.egypro.2013.06.421.

[95] Mustapha WF, Bolkesjø TF, Martinsen T, Trømborg E. Techno-economic comparison of promising biofuel conversion pathways in a Nordic context – Effects of feedstock costs and technology learning. Energy Convers Manag 2017;149:368–80. doi:10.1016/j.enconman.2017.07.004.

[96] Börjesson M, Grahn M, Ahlgren E. Transport Biofuel Futures in Energy-Economic Modeling – A Review. The Swedish Knowledge Centre for Renewable Transportation Fuels: Göteborg, Sweden: 2013.

[97] Brynolf S, Taljegard M, Grahn M, Hansson J. Electrofuels for the transport sector: A review of production costs. Renew Sustain Energy Rev 2018;81:1887–905. doi:10.1016/j.rser.2017.05.288.

[98] Goldmann A, Sauter W, Oettinger M, Kluge T, Schröder U, Seume J, et al. A Study on Electrofuels in Aviation. Energies 2018;11:392. doi:10.3390/en11020392.

[99] Mustapha WF, Kirkerud JG, Bolkesjø TF, Trømborg E. Large-scale forest-based biofuels production: Impacts on the Nordic energy sector. Energy Convers Manag 2019;187:93–102. doi:10.1016/j.enconman.2019.03.016.

[100] Sgobbi A, Nijs W, De Miglio R, Chiodi A, Gargiulo M, Thiel C. How far away is hydrogen? Its role in the medium and long-term decarbonisation of the European energy system. Int J Hydrogen Energy 2016;41:19–35. doi:10.1016/j.ijhydene.2015.09.004.

[101] Næss P, Jensen OB. Urban structure matters, even in a small town. J Environ Plan Manag 2004;47:35–57. doi:10.1080/0964056042000189790.

[102] Krumdieck S, Page S, Dantas A. Urban form and long-term fuel supply decline: A method to investigate the peak oil risks to essential activities. Transp Res Part A Policy Pract 2010;44:306–22. doi:10.1016/j.tra.2010.02.002.

[103] Forsberg J, Krook-Riekkola A. Supporting Cities' Emission Mitigation StrategieS: Modelling Urban Transport in a Times Energy System Modelling Framework. In Proceedings of the 17th International Conference on Urban Transport and the Environment, University of Rome 'La Sapienza', Rome, Italy, 5–7 September 2017; Ricci, S., Brebbia, C.A., Eds.; Wessex Institute: Ashurst, UK, 2017; pp. 15–25. doi:10.2495/UT170021.

[104] Sovacool BK, Noel L, Kester J, Zarazua de Rubens G. Reviewing Nordic transport challenges and climate policy priorities: Expert perceptions of decarbonisation in Denmark, Finland, Iceland, Norway, Sweden. Energy 2018;165:532–42. doi:10.1016/j.energy.2018.09.110.

[105] International Energy Agency. Personal Communication with Pierpaolo Cazzola, August 2017.

[106] Pfenninger S. Energy scientists must show their workings. Nature 2017;542:393–393. doi:10.1038/542393a.

[107] Balyk O, Andersen SK, Dockweiler S, Gargiulo M, Karlsson K, Næraa R. TIMES-DK: Technology-rich multi-sectoral optimisation model of the Danish energy system. Energy Strateg Rev 2019;23:13-22. doi.org/10.1016/j.esr.2018.11.003.18.

[108] Wikipedia. Electricity price area 2018. https://en.wikipedia.org/wiki/Electricity_price_area (accessed October 9, 2018).

[109] Eurostat. Energy balances 2018. https://ec.europa.eu/eurostat/web/energy/data/energy-balances (accessed December 1, 2018).

[110] DTU Transport. Danish National Travel Survey - dataset TU0615v1 from May 2006 to December 2015: 2016 (accessed September 10, 2017).

[111] Norwegian Centre for Research Data. Norwegian National travel Survey - dataset 2013/2014 2014. http://www.nsd.uib.no (accessed May 12, 2017).

[112] Transport Analysis. Swedish National Travel Survey - dataset 2011-2016 2018. https://www.trafa.se (accessed March 4, 2018).

[113] Danish Energy Agency, COWI. Alternative transport fuels. 2012.

[114] International Energy Agency. Technology Roadmap - Carbon Capture Storage. Paris, France: 2009.

[115] Brøndum Andersen S. How can the Nordic countries become CO_2-negative by 2040 - An energy system analysis with a focus on the Carbon Capture and Storage technology (Master's thesis). Technical University of Denmark, 2018.

[116] Danish Energy Agency (ENS). https://ens.dk (accessed December 5, 2017).

[117] Statistics Norway (SSB). https://www.ssb.no (accessed May 12, 2017).

[118] Statistics Sweden (SCB). https://www.scb.se (accessed May 12, 2017).

[119] Statistics Denmark (DST). StatBank Denmark. https://www.statistikbanken.dk (accessed December 5, 2017).

[120] Institute of Transport Economics - Norwegian Centre for Transport Research (TØI). https://www.toi.no (accessed December 10, 2018).

[121] Transport Analysis. https://www.trafa.se (accessed December 5, 2017).

[122] Swedish Energy Research Centre (Energiforsk). Personal Communication with Markus Wråke, 2017.

[123] Lehtilä A. TIMES Micro – Elastic Demand Functions Energy Systems Technology Analysis Programme (ETSAP). International Energy Agency (IEA); 2018. https://iea-etsap.org/docs/TIMES-Micro-Note.pdf

[124] Loulou R. ETSAP-TIAM: the TIMES integrated assessment model. part II: mathematical formulation. Comput Manag Sci 2008;5:41–66. doi:10.1007/s10287-007-0045-0.

[125] Nordic Council of Ministers (Norden). Reducing CO_2 Emissions from Freight. Copenhagen, Denmark: 2018.

[126] The Swedish National Road and Transport Research Institute. Vierth I, Mellin A. Svensk godsstudie baserad på nationell och internationell litteratur Internationell exposé-persontransporter. Linköping, Sweden: 2008.

[127] Rand Corporation. Dunkerley F, Wardman M, Rohr C, Fearnley N. Bus fare and journey time elasticities and diversion factors for all modes. Cambridge, UK: 2018.

[128] Oum TH, Waters WG, Yong JS. A survey of recent estimates of price elasticities of demand for transport. Washington: 1990.

[129] Victoria Transport Policy Institute. Litman TA. Understanding transport demands and elasticities: how prices and other factors affect travel behavior.

Canada: 2017.

[130] Fearnley N, Flügel S, Killi M, Gregersen FA, Wardman M, Caspersern E, et al. Triggers of Urban Passenger Mode Shift – State of the Art and Model Evidence. Transp Res Procedia 2017;26:62–80. doi:10.1016/j.trpro.2017.07.009.

[131] Transport Research Laboratory. Balcombe R, Mackett R, Paulley N, Preston J, Shires J, Titheridge H, et al. The demand for public transport: a practical guide. Workingham, UK: 2004.

[132] Pye S, Usher W, Strachan N. The uncertain but critical role of demand reduction in meeting long-term energy decarbonisation targets. Energy Policy 2014;73:575–86. doi:10.1016/j.enpol.2014.05.025.

[133] Rich J. The Weekday Demand Model in LTM – Model For Generation, Destination and Mode Choice. Kgs. Lyngby, Denmark: 2015.

[134] Beuthe M, Jourquin B, Geerts JF, Koul À Ndjang'Ha C. Freight transportation demand elasticities: A geographic multimodal transportation network analysis. Transp Res Part E Logist Transp Rev 2001;37:253–66. doi:10.1016/S1366-5545(00)00022-3.

[135] Nordic Council of Ministers (Norden). Mining in the Nordic Countries. Copenhagen, Denmark: 2015.

[136] Pinchasik DR, Hovi IB, Mjøsund CS, Grønland SE, Fridell E, Jerksjö M. Crossing Borders and Expanding Modal Shift Measures: Effects on Mode Choice and Emissions from Freight Transport in the Nordics. Sustainability 2020;12:894. doi:10.3390/su12030894.

[137] Ahanchian M, Gregg JS, Tattini J, Karlsson KB. Analyzing effects of transport policies on travelers' rational behaviour for modal shift in Denmark. Case Stud Transp Policy 2019;7:849–61. doi:10.1016/j.cstp.2019.07.010.

[138] Schafer A, Victor DG. The future mobility of the world population. Transp Res Part A 2000;34:171–205.

[139] Rich J, Holmblad PM, Hansen CO. A weighted logit freight mode-choice model. Transp Res Part E Logist Transp Rev 2009;45:1006–19. doi:10.1016/j.tre.2009.02.001.

[140] De Jong G, Schroten A, Van Essen H, Otten M, Bucci P. The price sensitivity of road freight transport - a review of elasticities. The Hague, Netherlands: 2010.

[141] The Swedish National Road and Transport Research Institute (VTI). Vierth I, Mellin A, Hylén B, De Jong G, Bucci P. Priselasticiteter som underlag för konsekvensanalyser av förändrade banavgifter för godstransporter. Linköping, Sweden: 2010.

[142] Rich J. Transport Models - From Theory to Practise. 6.0. Lyngby, Denmark: SelfPublished; 2015. doi:10.13140/RG.2.1.1093.1922.

[143] Loulou R, Lehtilä A, Kanudia A, Remme U, Goldstein G. Documentation for

the TIMES Model - Part II: Comprehensive Reference Manual. Energy Systems Technology Analysis Programme (ETSAP); 2016.

[144] ÅF Making Future. Översyn av Trafikverkets klimatscenarier. Stockholm, Sweden: 2018.

[145] Taljegard M, Thorson L, Odenberger M, Johnsson F. Large-scale implementation of electric road systems: Associated costs and the impact on CO 2 emissions. Int J Sustain Transp 2019:1–14. doi:10.1080/15568318.2019.1595227.

[146] C40 Cities Climate Leadership Group. https://www.c40.org/ (accessed October 21, 2019).

[147] European Commission. White Paper. Roadmap to a Single European Transport Area - Towards a competitive and resource efficient transport system. Brussels, Belgium: 2011.

[148] Argonne National Laboratory. Assessment of Vehicle Sizing, Energy Consumption, and Cost Through Large-Scale Simulation of Advanced Vehicle Technologies. Argonne, Illinois, USA: 2016.

APPENDIX A

This supplement material provides calculations steps and further details about the equations presented in Chapter 5.

Demand price functions integral

The demand price functions (second expression in Eq. (5.1)) can be integrated as follows:

$$\begin{aligned}
&\int_0^{DM_i(t)} p_i(t)\,dq = \int_0^{DM_i(t)} p_i^0(t)\cdot\left(\frac{q}{DM_i^0(t)}\right)^{\frac{1}{E_i(t)}} dq = \\
&= \frac{p_i^0(t)}{DM_i^0(t)^{\frac{1}{E_i(t)}}} \int_0^{DM_i(t)} q^{\frac{1}{E_i(t)}}\,dq = \frac{p_i^0(t)}{DM_i^0(t)^{\frac{1}{E_i(t)}}}\cdot\frac{DM_i(t)^{1+\frac{1}{E_i(t)}}}{\left(1+\frac{1}{E_i(t)}\right)}
\end{aligned} \tag{A.1}$$

Step-wise approximation in the LP

In Fig. A.1, a graphic representation of the step-wise approximation of the non-linear term $DM_i(t)^{\frac{1}{E_i(t)}}$ is shown, where three steps are used for both the up and low direction ($n_i(t)$ and $m_i(t)$).

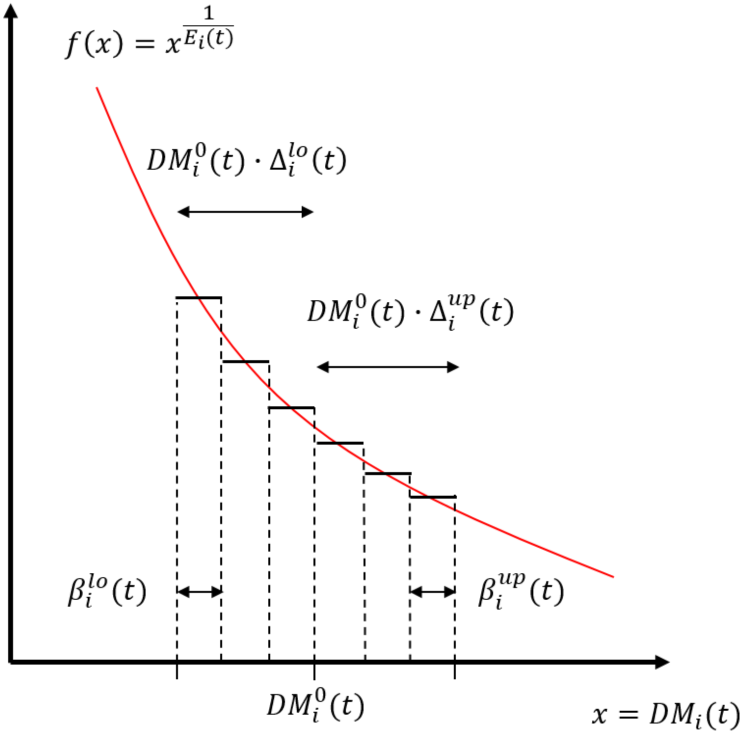


Fig. A.1. *Step-wise approximation of* $DM_i(t)^{\frac{1}{E_i(t)}}$. *Figure inspired from* [22].

Thanks to the step-wise approximation (Fig. A.1), the second term of the right-hand side of Eq. (5.6) can be rewritten as follows:

$$\begin{aligned}\left(1+\frac{1}{E_i(t)}\right)\cdot DM_i(t)^{\frac{1}{E_i(t)}}\bigg|_{DM_i^0(t)}\cdot\left(DM_i(t)-DM_i^0(t)\right)\\ =\left(1+\frac{1}{E_i(t)}\right)\\ \cdot\left[-\sum_{j=1}^{m}\left(DM_i^0(t)\right.\right.\\ \left.-\left(j-\frac{1}{2}\right)\beta_i^{lo}(t)\right)^{\frac{1}{E_i(t)}} sm_{j,i}(t)\\ \left.+\sum_{j=1}^{n}\left(DM_i^0(t)+\left(j-\frac{1}{2}\right)\beta_i^{up}(t)\right)^{\frac{1}{E_i(t)}} sn_{j,i}(t)\right]\end{aligned} \tag{A.2}$$

It is worth noticing that the multiplicative coefficients of the step variables within the summations represent the function $DM_i(t)^{\frac{1}{E_i(t)}}$ evaluated in the middle of each step (Fig. A.1). Thus, multiplying these coefficients with the respective step variables gives the approximated area subtended by the original function.

Eq. (A.2) can be rewritten in a more compact way as follows:

$$\begin{aligned}DM_i(t)^{1+\frac{1}{E_i(t)}} \cong DM_i^0(t)^{1+\frac{1}{E_i(t)}} - \sum_{j=1}^{m} AM_{j,i}(t)\cdot sm_{j,i}(t)\\ +\sum_{j=1}^{n} AN_{j,i}(t)\cdot sn_{j,i}(t)\end{aligned} \tag{A.3}$$

While Eq. (5.2) can be rewritten using Eq. (A.3) as follows:

$$
\begin{aligned}
Min \quad c^T \cdot X - \sum_i \sum_t PVF(t) \cdot & \frac{p_i^0(t)}{DM_i^0(t)^{\frac{1}{E_i(t)}} \cdot (1 + \frac{1}{E_i(t)})} \\
& \cdot \left(DM_i^0(t)^{1+\frac{1}{E_i(t)}} - \sum_{j=1}^{m} AM_{j,i}(t) \cdot sm_{j,i}(t) \right. \\
& \left. + \sum_{j=1}^{n} AN_{j,i}(t) \cdot sn_{j,i}(t) \right)
\end{aligned}
\tag{A.4}
$$

Finally, Eq. (5.7) can be easily obtained by expressing $AM_{j,i}(t)$ and $AN_{j,i}(t)$ explicitly and by rearranging the multiplicative factors of the brackets with the ones of the terms included within them.

Additional insights on $p_{j,i}^{\pm}(t)$

For simplicity reasons, in Fig. 5.2, $p_{j,i}^{\pm}(t)$ are represented as symmetric functions respect to the dashed line $p_i^0(t)$, though, they are not symmetric. For instance, when the elasticity $E_i(t)$ tends to 0^-, $p_{j,i}^{-}(t)$ approaches $+\infty$ at a faster pace than how $p_{j,i}^{+}(t)$ approaches 0^-. This is due to the nature of the elastic response assumed in Eq. (5.1), and it can also be noted by looking at Fig. A.1, where for a specific $E_i(t)$, the step height of decreasing steps increases with *j*, while for increasing steps decreases with *j*, though this occurs asymmetrically because of the exponential profile. Indeed, higher *j* entails for increasingly higher $p_{j,i}^{-}(t)$ and decreasingly lower $p_{j,i}^{+}(t)$ (Fig. 5.2).

APPENDIX B

This supplement material provides ulterior details regarding the TIMES-Nordic inputs mentioned in Chapter 4 and the analysis presented in Chapter 6.

Modal technical features

In this Section, the technical features assumed for all modes involved in the elastic modal shift are presented. The data are provided for the existing technologies populating the fleet in the BY (2010). Such modal features characterise also the relative future technologies defined for the same mode in the same region (e.g. occupancy, load factors and mileages). However, some techno-economic parameters characterising future technologies are assumed to improve thanks to research and development. For instance, future efficiencies are calculated by multiplying the BY values with improvement factors (obtained e.g. from [113,148]), which are heterogeneous across modes and technologies. For brevity reasons, efficiencies characterising future technologies are not reported in this supplementary material. Moreover, when technical features are presented only for a few regions, it means that in the BY such technology is defined only for the mentioned regions. However, for some cases, the same technology type is available for future investments in all regions of the model.

As mention in Chapter 4, modal technical features are obtained based on national transport statistics. However, the availability of data vary from mode to mode and from country to country, thus different approaches are required to characterise the different modal fleet in the different regions. For instance, in the case of cars, the stock can easily be found in national transport statistics (such as those mentioned in Chapter 4) by age class and by fuel type and for a few years after the BY. This allows to declare the number of vehicles per engine type and to assume a decommissioning factor based on the age of the stock. However, for a specific type of car, the stock is heterogeneous in terms of model types (or size) and age, thus the efficiency, which is usually assumed from a technology catalogue (such as [113]) is adjusted in order to match the yearly national fuel consumption for that mode (calibration based on national energy balances). Besides, the mileage for a specific car type in a specific region is obtained by multiplying the national transport work of the selected car type (expressed in Mkm) by the share of car mobility demand defined in that region, then such value is divided by the stock of the specific car type assumed for that region. The occupancy factor is obtained by dividing the total national car mobility demand (Mpkm) by the national transport work (expressed in Mkm). This is the reason why the occupancy factors assumed for cars vary across countries but not across regions belonging to the same country.

Similar approaches are carried out to characterize the technical features of the other transport modes defined in the model. However, in cases where data availability is limited, a set of assumptions is required. For instance, in the case of international freight ships, the stock for each country is obtained from the National registry for international ships. Even though, such vessels operate across different countries and their registration to a specific flag is not representative for where they operate. The mileage is estimated assuming around 230 operating days at sea per year and an average cruise speed of 22 knots, while the load factor is calculated starting from the assumed stock and mileage to match the BY modal transport demand. In these cases, where data availability is limited, the modal technical features obtained are affected by a larger degree of uncertainty.

In Table B.1, occupancy, load factors and mileages assumed for each mode in the BY (2010) are presented per technology type and by region.

Table B.1. *Occupancy, load factor and mileage assumed for each mode in the BY per technology type. *Natural gas ICE busses are defined only in SE1 – SE4 in the BY.*

Mode	**Technology**	**Region**	**Occupancy or load factor**	**Mileage**
	Engine type		Person or tonnes / vehicle	Maximum km travelled per year
Car	**Diesel ICE**	DKE	1.55	21065
		DKW	1.55	23723
		NO1	1.81	17265
		NO2	1.81	15946
		SE1–SE4	1.72	18890
	Gasoline ICE	DKE	1.55	12916

		DKW	1.55	14546
		NO1	1.81	11984
		NO2	1.81	12536
		SE1–SE4	1.72	11323
	Natural gas ICE	DKE–DKW	1.55	18000
		NO1–NO2	1.81	18000
		SE1–SE4	1.72	18000
	BEV	DKE–DKW	1.55	14000
		NO1–NO2	1.81	14000
		SE1–SE4	1.72	14000
	Gasoline-blended ICE	SE1–SE4	1.72	11323
Moped	**Gasoline ICE**	DKE–DKW	1.00	1348
		NO1–NO2	1.00	1158
		SE1–SE4	1.22	1319
Moto	**Gasoline ICE**	DKE–DKW	1.05	3013
		NO1–NO2	1.05	7602
		SE1–SE4	1.22	2698
Bike		DKE–DKW	1	1373
		NO1–NO2	1	1163
		SE1–SE4	1	435
Walk		DKE–DKW	1	301
		NO1–NO2	1	625
		SE1–SE4	1	343
Bus	**Diesel ICE and natural gas ICE***	DKE–DKW	11.47	46176
		NO1–NO2	11.14	20205
		SE1–SE4	9.13	55272
Coach	**Diesel ICE**	DKE–DKW	10.16	43172
		NO1–NO2	10.16	22163
		SE1–SE4	9.13	55272
Metro	**Electric**	DKE	49.57	141794
		NO1	45.78	120000
		SE3	137.49	24542
Train	**Diesel**	DKE	100.76	100671
		DKW	75.15	180733

		NO1	88.10	145899
		NO2	85.84	149739
		SE1 – SE4	42.72	67903
	Electric	DKE	100.76	100671
		DKW	75.15	180733
		NO1	88.10	145899
		NO2	85.84	149739
		SE1–SE4	118.95	71643
Light rail	**Electric**	DKE	76.17	121225
		NO1	39.05	50000
		SE3	33.57	33318
Truck	**Diesel ICE**	DKE	15.63	45000
		DKW	12.15	45000
		NO1	13.88	50000
		NO2	13.88	73000
		SE1–SE4	7.79	48228
Freight rail	**Diesel ICE**	DKE	180.00	26000
		DKW	180.00	17500
		NO1–NO2	373.14	59724
		SE1–SE4	552.78	11885
	Electric	DKE	180.00	26000
		DKW	180.00	17500
		NO1–NO2	373.14	59724
		SE1–SE4	552.78	117266
Freight ship international	**Diesel and heavy fuel oil ICE**	DKE–DKW	1778.49	220565
		NO1	737.07	220565
		NO2	736.93	220565
		SE1–SE4	1778.49	220565
Freight ship national	**Diesel and heavy fuel oil ICE**	DKE–DKW	133.18	99555
		NO1–NO2	198.78	125029
		SE1–SE4	133.18	99555

In Table B.2, efficiencies assumed for each mode in the BY are presented per technology type, per region and by distance classes (*k*). Indeed, in order to emulate driving patterns effect on fuel economy, a different efficiency is applied by the model depending on which demand category is supplied by the modal technology. For some modes, such characterization is not applied, when this is the case, efficiencies are shown regardless of the distance classes. For cars, efficiencies are shown only for the BY, though, thanks to the data available for this mode, updated values are declared also for the year 2012. The efficiencies for bike and walk are not presented for obvious reasons.

Table B.2. *Efficiencies assumed for each mode in the BY per technology type and by distance classes (k). **Gasoline-blended ICE cars are defined only in SE1 – SE4 in the BY.*

Mode	**Technology**	**Region**	***k***	**Efficiency**
	Engine type			Mvehicle*km/PJ
Car	**Diesel ICE**	DKE–DKW	L	442.60
		DKE–DKW	M	361.74
		DKE–DKW	S	279.26
		DKE–DKW	XS	220.66
		NO1–NO2	L	542.84
		NO1–NO2	M	443.11
		NO1–NO2	S	342.08
		NO1–NO2	XS	270.30
		SE1–SE4	L	382.44
		SE1–SE4	M	344.42
		SE1–SE4	S	265.20
		SE1–SE4	XS	210.10
	Gasoline ICE, natural gas ICE and gasoline-blended ICE**	DKE–DKW	L	465.34
		DKE–DKW	M	380.32
		DKE–DKW	S	293.61
		DKE–DKW	XS	231.99
		NO1–NO2	L	485.19
		NO1–NO2	M	396.05
		NO1–NO2	S	305.75
		NO1–NO2	XS	241.59
		SE1–SE4	L	385.03
		SE1–SE4	M	346.75

		SE1–SE4	S	267.00
		SE1–SE4	XS	211.52
	BEV	DKE–DKW		1431.74
		NO1–NO2		1431.74
		SE1–SE4		1431.74
Moped	**Gasoline ICE**	DKE–DKW		1265.82
		NO1–NO2		722.54
		SE1–SE4		1265.82
Moto	**Gasoline ICE**	DKE–DKW	L	641.03
		DKE–DKW	M	781.86
		DKE–DKW	S	762.20
		NO1–NO2	L	437.53
		NO1–NO2	M	533.65
		NO1–NO2	S	520.23
		SE1–SE4	L	641.03
		SE1–SE4	M	781.86
		SE1–SE4	S	762.20
Bus	**Diesel ICE**	DKE–DKW	L	115.30
		DKE–DKW	M	102.85
		DKE–DKW	S	81.35
		DKE–DKW	XS	81.35
		NO1–NO2	L	57.65
		NO1–NO2	M	51.42
		NO1–NO2	S	40.68
		NO1–NO2	XS	40.68
		SE1–SE4	L	92.24
		SE1–SE4	M	82.28
		SE1–SE4	S	65.08
		SE1–SE4	XS	65.08
	Natural gas ICE	SE1–SE4	L	54.20
		SE1–SE4	M	48.34
		SE1–SE4	S	38.24
		SE1–SE4	XS	38.24
Coach	**Diesel ICE**	DKE–DKW	L	115.30
		DKE–DKW	M	102.85

		DKE–DKW	S	81.35
		NO1–NO2	L	57.65
		NO1–NO2	M	51.42
		NO1–NO2	S	40.68
		SE1–SE4	L	92.24
		SE1–SE4	M	82.28
		SE1–SE4	S	65.08
Metro	**Electric**	DKE		74.07
		NO1		74.07
		SE3		20.95
Train	**Diesel ICE**	DKE–DKW		18.50
		NO1–NO2		18.50
		SE1–SE4		29.16
	Electric	DKE–DKW		23.39
		NO1–NO2		18.71
		SE1–SE4		20.95
Light rail	**Electric**	DKE		34.85
		NO1		34.85
		SE3		20.95
Truck	**Diesel ICE**	DKE–DKW		63.38
		NO1–NO2		48.54
		SE1–SE4		63.38
Freight rail	**Diesel ICE**	DKE–DKW		5.78
		NO1–NO2		9.63
		SE1–SE4		5.44
	Electric	DKE–DKW		12.49
		NO1–NO2		16.65
		SE1–SE4		12.27
Freight ship international	**Diesel and heavy fuel oil ICE**	DKE–DKW		3.34
		NO1–NO2		7.98
		SE1–SE4		3.34
Freight ship national	**Diesel and heavy fuel oil ICE**	DKE–DKW		5.50
		NO1–NO2		6.04
		SE1–SE4		12.39

TIMES-Nordic analysis

In Table B.3, alternative substitution elasticities σ_k are calculated by assuming different modal elasticities in light of the discussion outlined in Section 6.4.2. The elasticity for car, walk, bike, moped and moto obtained based on [133] are assumed without applying any multiplicative factors, while an average elasticity value for freight ship is adopted from [139].

***Table B.3. Left side**: long-term own-price elasticities assumed for each transport mode with original sources. **Right side**: substitution elasticities assumed for each aggregate k. *Sources indicate the references used to identify the modal elasticities, for assumptions and calculations steps see Paper **IV**.*

	Mode	**Elasticity**	**Source***	k *Aggregate*	σ_k *Substitution elasticity*
Passenger	Bike	-0.19	[133]	***XS***	-0.35
	Bus	-1.1	[127,131]		
	Car	-0.43	[133]		
	Coach	-1.5	[127,131]		
	Light Rail	-1.2	[131]	***S***	-0.46
	Metro	-0.7	[131]	***M***	-0.53
	Moped	-0.43	[133]		
	Moto	-0.43	[133]	***L***	-0.69
	Train	-1.2	[129]		
	Walk	-0.24	[133]		
Freight	Rail	-1.2	[128]	***NL***	-0.84
	Ship	-0.13	[139]		
	Truck	-1.1	[128]	***I***	-0.58

It is worth mentioning that the modal elasticity for freight ship is obtained from [139] as an average across the twelve commodity groups for which direct elasticities with respect to travel cost are provided. Lastly, the type considered is “Comp” and the mode “Sea”.

Since car and ship are the modes with the largest transport demands defined in TIMES-Nordic respectively for the passenger and freight sub-sectors, a variation in their modal elasticities has a large impact on the substitution elasticities σ_k. Compared to the values presented in Section 6.2.1, a car elasticity three times smaller entails for around halved substitution elasticities, while for freight the same impact on substitution elasticities is reached by a ten times lower elasticity for ship.

APPENDIX C

Paper I: Global outlook for the transport sector in energy scenarios

Paper II: Energy Scenario Analysis for the Nordic Transport Sector: A Critical Review

Paper III: Modelling transport modal shift in TIMES models through elasticities of substitution

Paper IV: The role of modal shift in decarbonising the Scandinavian transport sector: Applying substitution elasticities in TIMES-Nordic

Paper I

Global outlook for the transport sector in energy scenarios

Chapter 3

Global outlook for the transport sector in energy scenarios

Raffaele Salvucci, DTU Management
Jacopo Tattini, International Energy Agency

Introduction

Transport is an important driver of social and economic development, as it connects people across different regions and enables the exchange of goods. However, transport is also responsible for several externalities. Today the transport sector accounts for almost one-third of final energy consumption [1]. It is also a major contributor to global warming, accounting for approximately one-third of global energy-related CO_2 emissions, and is a primary responsible for urban air pollution. Moreover, the transport sector currently presents the least diversified portfolio of energy resources among all energy sectors, relying mainly on oil and accounting for nearly two-thirds of total oil consumption.

Given the increasing rate of urbanization globally, which will lead to two-thirds of the global population living in urban areas by 2050 [2], cities are expected to play a major role in terms of global energy consumption and energy-related environmental emissions. The trend towards urbanization represents both a challenge and an opportunity for the transport sector's sustainable transition. On the one hand, growing population and income levels in urban areas are key drivers of rising transport activity. On the other hand, thanks to their high population densities and urban transport patterns, which are normally characterized by trips of short distances, cities can be leaders in the utilization of non-motorized forms of transport and public transport, as well as in the uptake of sustainable transport technologies such as electric vehicles (EVs) [2]. In addition, cities are often more ambitious than national governments in committing themselves to more ambitious environmental goals [3]. This, for instance, is the case in the Nordic capitals, which are already leaders in terms of sustainable mobility, each one with its own peculiarities: public transport (Stockholm), cycling (Copenhagen), light-duty EVs (Oslo) and EV buses (Helsinki) [4].

This chapter first sets out the situation in the current global transport sector, highlighting the main challenges related to its sustainable transition and reflecting on which strategies should be put in practice to mitigate the sector's externalities. Then it describes future outlooks for the global transport sector according to the International Energy Agency (IEA) before concluding by recommending key policies for decarbonizing transport.

Global challenges in transportation

Given the relevance of transport externalities, changing the current transport paradigm is of major importance to the tasks of mitigating climate change, alleviating air pollution and enhancing energy security. However, several elements suggest that finding a sustainable transition for the transport sector is particularly challenging. Despite the wide set of policy measures implemented globally to reduce transportation carbon intensity and reliance on oil, CO_2 emissions from the transport sector increased by about 2% a year from 2010 to 2016 [5]. The continued growth in carbon emissions from the transport sector is attributable to the fact that the growth in transport activity resulting from increasing populations, gross domestic product (GDP) and income levels is proceeding at a faster pace than improvements to the performance of transport technologies. Emissions from the aviation and maritime sectors continue to grow, suggesting that more cooperative international efforts are needed to reverse the trend. At the same time, emissions from all modes of road transport (cars, buses, trucks and two-wheelers) have also kept on rising, attributable in part to the preference of car buyers for bigger and heavier vehicles worldwide [6]. In Europe, this trend sums up to decreasing sales of diesel cars, which have lower CO_2 emissions than gasoline cars, but are worse in emitting pollutants. Overall these developments are outweighing the positive effects of rising sales of hybrid and electric cars and in 2018 led to the average fuel economy improvements of light-duty vehicles slowing down to 1.4% per year, the lowest rate since 2005 [6].

Some of the main challenges hindering the sustainable transition of the transport sector are related to the facts that:

- Transport activity is tightly coupled with gross domestic product (GDP) and to population and income levels, factors that are increasing in many countries worldwide. By 2050, the global population is expected to have grown by 30% compared to 2015 [2]. In particular, given the increase in the urbanization rate, two-thirds of the global population will be living in cities, the same place where countries' economies will develop the most, especially in emerging economies. Therefore, due to increases in prosperity, urban populations will potentially be responsible for higher consumption levels of goods and services, more transport activity and greater ownership of private vehicles [2].
- Sustainable transport technologies are already available on the market, but their high investment costs are slowing their widespread acceptance and thus call for policy support [7]. Moreover, the adoption of low-carbon technologies is being hampered by the slow turnover rate of existing vehicle fleets and the lock-in effect derived from the existing infrastructure.
- The growing demand for flexible freight transport implies a greater utilization of trucks, especially in emerging economies, where the road infrastructure is rapidly expanding, leading to trucks being regarded as among the fastest growing sources of global oil demand [8].
- The increasing penetration of e-commerce and digital technologies such as Mobility-as-a-Service (MaaS), sharing mobility and autonomous vehicles might result in additional overall transport activity, with potentially negative impacts on energy consumption and emissions from transport [9].

The successful low-carbon transition of the transport sector requires major policy and technology developments and relies on the ability of policy-makers to identify the challenges and to implement an all-encompassing set of measures aiming at addressing them.

Decarbonization strategy: avoid/shift/improve

Getting transport on track to meet global environmental goals such as the Paris Agreement [10] requires putting into practice a broad set of measures, summarized in the International Energy Agency's slogan *Avoid, Shift, Improve*. *Avoid* entails mitigating transport activity by limiting the number of trips and reducing their distances. *Shift* consists in limiting the reliance on carbon-intense modes of transport by enhancing the use of public transportation and non-motorised modes of transport. *Improve* implies enhancing vehicle efficiency by adopting more efficient power trains, replacing oil-based fuels with low-carbon fuels, increasing vehicles' occupancy and load factors and light weighting. This section describes the main recent developments and trends relative to the three key pillars of transport decarbonization.

Avoid

The measures included in the category *Avoid* are those that aim at reducing energy consumption and emissions from transport primarily through a reduction in activity (measured in passenger-kilometres or tonne-kilometres). Such measures enable people to satisfy their daily needs while avoiding taking a trip or limiting its distance and ensuring that goods are delivered while minimizing their overall distance. Urban design is an important driver of transport activity. Compact cities or neighbourhoods that include both residential dwellings and commercial or business activities enable shorter trips [2]. A wider adoption of intelligent transport systems (ITS) can also reduce total distances travelled by suggesting shorter routes and can mitigate congestion by recommending less busy routes. Teleworking and virtual mobility are increasingly being adopted by companies and have the potential to reduce their employees' transport activity levels, also resulting in less congested roads and less busy public transport during peak hours. A wider deployment of logistical hubs and the concurrent enhancement of logistical services can improve the overall freight supply chain, resulting in lower freight transport activity.

Shift

The actions grouped under the category *Shift* aim at reducing transport externalities by replacing carbon-intense modes of transport with low-carbon ones. Figure 1 illustrates the rationale behind shift measures: rail has the lowest energy intensity in the passenger transport sector and the second lowest (after shipping) in freight transport [11]. Therefore, shifting transport activity from private modes of transport or aviation to public transport enables energy consumption to be limited significantly.

So far, shift policy levers have mainly been limited to urban areas, as reflected by the several targets on the modal share of public transport in the NDCs of several countries [12]. However, shift policy measures generally do not target as much freight and intercity passenger transport.

Proper land-use planning that takes into account integrating the transport sector with the overall urban environment can foster the utilization of active modes of transport such as 'bike and walk' and increase public transport ridership. Transit-oriented development should be the urban paradigm for fast-growing cities, facilitating access to public transport and shorter trips.

Figure 1 shows that rail can play an important role in limiting both energy consumption and the environmental impacts of transport. Enhancing the role of rail in the overall transport system relies on three pillars [11]:

- Minimizing the cost of transport services by maximizing use of the rail network, to be achieved by integrating rail with the different mobility options, improving interoperability and widely adopting digital technologies.
- Maximizing revenues from rail systems, not by increasing tariffs, but by capitalizing on the capacity of railways stations to aggregate passengers, e.g. developing commercial activities in stations and capturing the increase in residential property values in the proximity of stations.
- Reflecting in the price of the transport modes the actual environmental impacts generated, e.g. through congestion charging, fuel taxes, vehicle registration taxes or road pricing.

Improve

The measures included in the category *Improve* are those that aim at reducing the energy intensity of transport by deploying low- and zero-emissions vehicles and replacing carbon-intense fuels with low-carbon fuels. The size of the global electric vehicles fleet is increasing rapidly. The stock of electric cars at the end of 2018 reached 5.1 million globally [13], 45% of which was located in China (see Figure 2). Sales of electric cars were about 2 million in 2018, up 68% compared to 2017 and achieving a 2.7% sales share globally.

While China leads the electric mobility sector in absolute numbers, Norway and Iceland have the highest sales shares, reaching 46% and 11% respectively in 2018. Cities that are experiencing a particular surge of EVs include Shenzhen (China), whose bus fleet has been completely electrified, and Oslo (Norway), where 55% of car sales were electric last year.

Global biofuel production in 2018 grew by 7% with respect to the previous year, reaching about 3.7 EJ (152 billion litres). The IEA expects such production to grow at 3% per year in the next five years [14]. Brazil is the global leader in biofuel production and consumption, reaching record levels of bio-diesel and ethanol production in 2018. The consumption of biofuels in the United States and Europe still occurs in the form of blended fuel additives to fossil fuels at low percentages.

While an increasing portfolio of low-carbon technologies is becoming available for short-distance inland transport, the shipping and aviation sectors are still facing a slow uptake of clean technologies and are proving to be the most difficult to decarbonize. The low energy density of batteries constitutes the main hurdle to the electrification of aviation, long-distance road transport and shipping. Currently, biofuels, synthetic fuels or hydrogen seem more attractive low-carbon solutions for these sub-sectors, as long as their production chains follow sustainability criteria. The low-carbon transition of the aviation sector is being encouraged through the Carbon Offsetting and Reducing Scheme for International Aviation (CORSIA), the regulatory framework that aims to stabilize GHG emissions from the aviation sector by 2020 [15]. For the shipping sector, in 2018 the International Maritime Organization approved the target of reducing its GHG emissions by 50% by 2050 with respect to 2008 levels [16]. However, the policy measures needed to reach this target have not yet been identified. The only binding regulatory framework is still the EEDI, a fuel-efficiency standard mandating a minimum improvement of energy efficiency for new ships [17] and a policy imposing a cap of 0.5% on the sulphur content of maritime fuels [18]. The latter policy is pushing ships to switch from burning heavy fuel oil (HFO) to equipping themselves with scrubbers, maritime diesel, biofuels, LNG and low-sulphur fuel oil [19]. Ammonia and hydrogen are also being looked at with growing interest for their potential to serve as low-carbon fuels in the shipping sector and are expected to play a growing role in addressing CO_2 and local pollutant emissions [20].

Global transport outlook

The future evolution of the global transport sector is analysed here through the lens of the International Energy Agency's two key scenarios: the New Policies Scenario (NPS) and the Sustainable Development Scenario (SDS). The NPS investigates how the global energy sector will evolve in the light of officially declared policy measures and regulatory frameworks, including government commitments in the Nationally Determined Contributions under the Paris Agreement, and taking into account the development of known technologies [1]. The SDS describes how the future energy and transport system

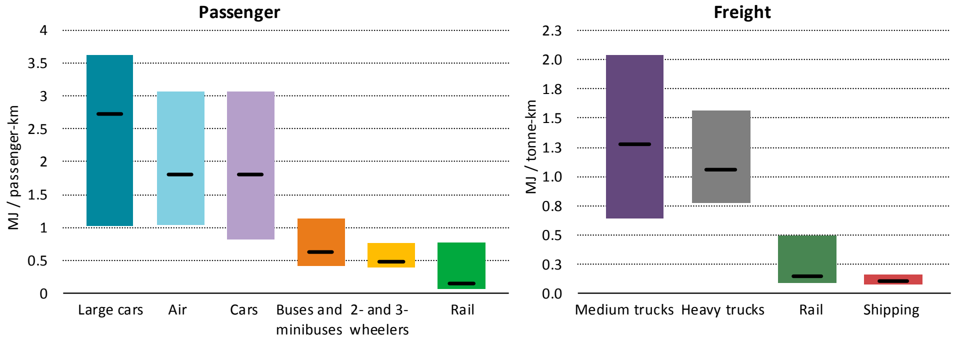


Figure 1. Comparison of the energy intensities of different modes of transport (passenger and freight)

Notes: The boxes indicate the range of average energy intensity in various countries, while the horizontal lines represent the world averages. Source: [11].

should evolve to be in line with the Paris Agreement, in parallel with achieving a drastic reduction in air pollution and broader energy access.

Transport in the IEA's New Policies Scenario

Under the NPS, transport energy consumption growth is contained at around 30% despite the strong increase in mobility demand (Figure 3), passing 150 EJ in 2040, up from about 120 EJ today. Oil is projected to account for less than half of the growth in transport energy consumption by 2040. Electricity consumption grows around five-fold, and biofuels and gas three-fold each by 2040 compared to 2017. However, transport continues to rely significantly on oil, which in 2040 will account for 82% of total energy consumption, while transport CO_2 emissions will increase by 20% compared to today.

Oil consumption from cars peaks in the 2020s due to the assumed improvements in fuel efficiency and the increased reliance on biofuels and electricity. On the other hand, trucks, aircraft and ships will contribute to the overall rise in global oil demand [1]. Emerging economies are expected to drive the increase in oil consumption due to their expected slower deployments of efficiency measures and low-carbon fuels compared to OECD countries.

With an additional forty million vehicles per year, the global car fleet in 2040 will have grown by 80% compared to today, reaching two billion cars. China and India will be responsible for 60% of this growth. Under the NPS, the average efficiency of a gasoline car in 2040 reaches 6.6L/100 km (vs 9.9L/100 km of today). Energy-efficiency measures and the uptake of EVs will limit the increase in energy use from the car stock to less than 20% despite the 80% increase in the global car fleet [1]. In 2040, around 300 million electric cars, 740 million electric bikes, scooters and rickshaws, 30 million electric trucks and 4 million electric buses will be deployed under the NPS [1]. China keeps its leading role in the electric mobility sector, accounting for 40% of electric cars and 60% of electric buses in the world.

Overall, road transport remains a major consumer of oil up to 2040 under the NPS, accounting for an increase of around 8 EJ with respect to 2017. Stringent fuel-economy and emissions standards, improvements in engines, hybridization and fuel switching to biofuels and natural gas are key measures to avoid the expected additional 40 EJ of oil demand, while introducing EVs avoids 10 EJ. The most significant mitigation measures are the improvements in vehicle and logistical efficiencies, which alone avoid 32 EJ of additional oil demand [1].

Trucks are the main responsible for the growing oil demand in the road sector (8 EJ), due to an increase in road freight activity of 3.1% per year. Energy savings in trucks, which avoid around 11 EJ of additional demand growth, come from both improvements in logistics, leading to increased load per vehicle, and engine enhancements [1]. Under the NPS, the average efficiency of a new heavy-duty truck in 2040 will have improved by 15% compared to today. The consumption of alternative fuels in trucks displaces more than 4 EJ of oil demand in 2040, while electric trucks have a lower impact (around 1.3 EJ).

In the aviation sector, the increase in activity largely offsets energy efficiency and biofuels, resulting in an overall increase of oil demand of 50%, reaching 21 EJ in 2040. In the shipping sector, the IMO regulation limiting the sulphur content of marine fuels [18] pushes away

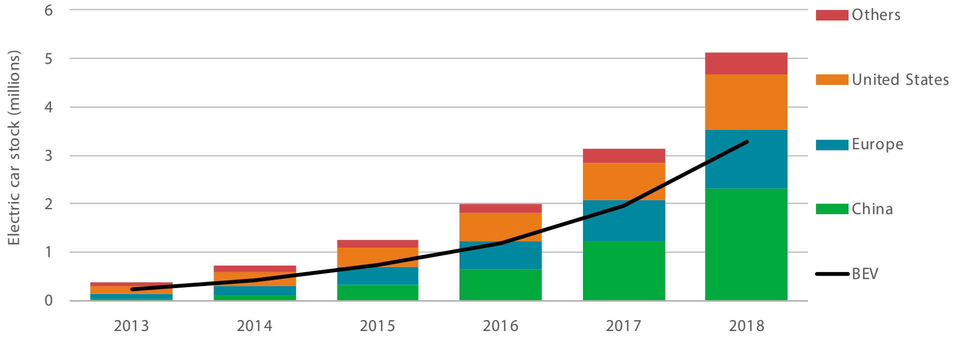


Figure 2. Passenger electric car stock in main markets, 2013-2018
Source: [13].

high-sulphur fuel oil, which will account for only for 25% of fuel use in 2040 (all used with scrubbers). On the other hand, the share of low-sulphur fuel oil and marine gasoil increases to 60%, while liquefied natural gas (LNG) grows its market share moderately [1].

The use of renewables in the overall transport sector increases gradually, reaching 8% of the fuel mix in 2040, more than double today's share (3.5%). Thanks to more efficient combustion engines, biofuels deliver more useful energy, while the contribution of renewable electricity increases as the deployment of EVs rises and the growth in electricity generation from renewables expands. Renewable-based electricity in 2040 accounts for 25% of renewable energy use in transport compared with today's 10%. China accounts for 40% of such growth, followed by the European Union (25%), India and the United States (<10% each) [1]. The use of biofuels increases worldwide at a rate of 5% each year until 2025, and of 3.5% between 2025 and 2040 as the use of gasoline and diesel levels off. This is particularly true for the European Union, where transport biofuel consumption plateaus after 2030 [1].

Under the NPS, total energy-related CO_2 emissions rise by 10% in 2040 compared to 2017 levels. Most of this growth comes from gas and oil, while coal remains the largest source of emissions in 2040. CO_2 emissions from the transport sector grow to 9.6 Gt in 2040, 20% more than today. In the road transport sector, EV uptake and improvements in vehicles and logistical efficiencies limit the growth in CO_2 emissions to 15%, while for other sub-sectors such growth reaches 40%. On the other hand, emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_x) and fine particulate matter (PM2.5) decline [1]. The increase in energy-related CO_2 emissions under the NPS, together with non-energy-related GHG missions coming from other sectors, would lead to a global temperature rise of 2.7°C by 2100, not in line with the Paris Agreement, which aims at a 1.5-2°C maximum rise [10]. The energy-related CO_2 emissions resulting from the NPS's assumptions are within the levels declared by countries' Nationally Determined Contributions. Within this scenario, countries result to be on track to deliver what they promised, but these commitments are far from being sufficient to limit the rise in average global temperature in line with the Paris Agreement.

Steering transport towards a sustainable transition

Under the SDS, final energy consumption from transport peaks in 2025 and then gradually reduces despite the increase in mobility demand. Electricity plays a larger role than in the NPS: its consumption in transport grows by 11% yearly on average, mainly driven by the strong uptake of EVs, which in 2040 accounts for more than 900 million cars. The combination of electrification and strong improvements to ICE fuel economy contributes to reducing oil demand in 2040 by approximately 40% compared to 2018. The SDS incorporates a shift to more efficient transport modes, such as from cars to public transport and non-motorized modes and avoid measures, involving urban design and reductions of trip frequencies and distances. Together, these measures facilitate the sustainable transition of the transport sector, accounting for a 3% decrease in transport CO_2 emissions by 2040 [1].

Oil demand peaks in almost all countries before 2030, except for India and sub-Saharan Africa, which reach their peaks later. Half of the global car fleet will be electric in 2040, while gasoline and diesel cars will be 40%

more efficient than today. A quarter of buses become electric by 2040, and 20% of the fuel consumed by trucks is low or zero carbon fuel. Overall, road transport energy consumption decreases by more than 38 EJ compared to today. Oil demand in aviation drops by 1.7 EJ, thanks to enhanced efficiency measures and an increasing penetration of biofuels, which in 2040 accounts for 2.8 EJ. Moreover, hydrogen-based fuels start to appear progressively in the shipping sector [1].

Power generation in the SDS is almost entirely decarbonized. Renewables are responsible for two-thirds of electricity generation, nuclear for 13%, while coal power plants, which are mostly equipped with carbon capture utilization and storage devices, account for only 5% [1].

Under the SDS, energy-related CO_2 emissions peak in 2020 and then decrease by more than 45% in 2040 compared to today. Despite the strong reduction in emissions, transport remains the largest emitter among all sectors, followed by industry. However, global energy-related CO_2 emissions are consistent with a long-term average increase in temperature of 1.7-1.8°C above pre-industrial levels, just within the limits laid down in the Paris Agreement. Moreover, NO_x emissions from transportation fall by 50% due to fuel switching and pollution control measures, while almost 25% of particulate emissions come from sources unrelated to combustion, such as brake and tyre abrasion [1].

The SDS shows that the large adoption of the avoid/shift/improve decarbonization strategy in transport can reduce energy consumption and put transport emissions on track for being aligned with the Paris Agreement's objectives. However, the transition should be put in motion within the next decade so as to avoid the need for stricter and more costly measures at a later stage. The main mitigation levers include regulatory measures to reduce the frequency, distance and reliance on energy-intensive modes of transport, a shift towards more efficient modes of transport and the adoption of energy-efficient technologies for vehicles and fuel production. In order to reach the SDS goals, progress in transport efficiency must double compared to the average rate seen since 2000.

Conclusions and recommendations

Transport is responsible for several externalities and today accounts for about one-third of energy-related CO_2 emissions. The future development of the transport sector envisioned in the IEA's New Policies Scenario (NPS) highlights that so far the officially declared policies and regulatory framework are not sufficient to steer energy consumption and CO_2 emissions towards a decreasing trend, and that actually CO_2 emissions are projected to continue growing [1]. Clearly, the NPS is not in line with a trajectory of CO_2 emissions that would enable the Paris Agreement to be achieved. This calls for the deployment of a more ambitious set of policy measures as envisioned in the Sustainable Development Scenario (SDS).

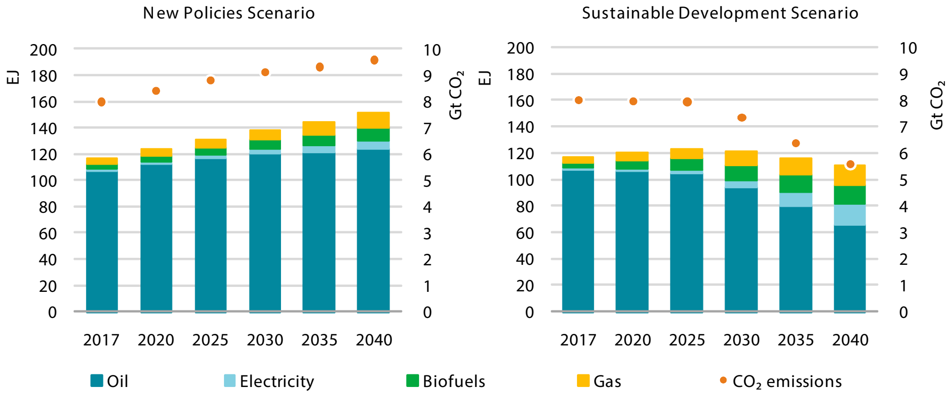


Figure 3. Final energy demand and CO2 emissions from transport by scenario, 2017-2040

Notes: The values for 2020 are obtained from linear interpolation between 2017 and 2020. Source: [1].

The strategy of putting the transport sector on track to meet the Paris Agreement rests on the following three pillars:

- Managing travel demand to limit the frequency and distance of trips (Avoid measures)
- Promoting low-carbon modes in order to spur a shift from private modes of transport and aviation (the most carbon-intense ones) to public transport and non-motorized modes (Shift measures)
- Rapidly scale up the offer and facilitate the adoption of efficient transport technologies, and increasing the availability of low-carbon fuels (Improve measures)

A comprehensive policy portfolio is recommended for implementation at several jurisdictional levels, international, national, subnational and urban. Fiscal policies can steer the decisions of transport users to be more in line with the overarching decarbonization targets. First of all, incentives for fossil fuels should be rapidly phased out and fuel taxes should incorporate the externalities incurred by consuming them. These measures would enhance the attractiveness of efficient and low-carbon vehicles and potentially lead to more efficient driving, to shifts towards low-carbon modes or to not taking trips at all [21]. Differentiated vehicle purchase taxes that reflect the environmental performances of different vehicles in respect of both CO_2 and pollutant emissions are an important mean of fostering consumers' adoption of energy-efficient and zero-emissions vehicles [7]. As the vehicle fleet becomes progressively more electric and the exchequer revenue from fuel taxes shrinks, a possible solution for financing the maintenance of transport infrastructure is the timely introduction of road pricing [13].

Regulatory measures should be implemented in parallel with fiscal levers to foster the supply and adoption of low-carbon vehicles. Zero-emission vehicle mandates such as those in place in ten states of the USA and the New Energy Vehicle mandate in China have proved effective in pushing original equipment manufacturers (OEMs) to develop and offer an increasing number of EV models [13]. Progressively tightening fuel economy standards is also a useful policy in reducing specific (per kilometre) vehicle emissions [6]. As new technologies and new fuels gain market shares, it is important to adopt broader sets of regulatory policies that do not consider just tailpipe emissions, but also upstream emissions related to fuel production and distribution (the 'well-to-wheel' perspective). Eventually, the regulatory framework can even extend beyond the vehicle operation phase, encompassing also emissions related to vehicle manufacturing and material extraction [13;21]. Most important, it is essential to ensure that policy packages are consistent with climate pledges. While these recommendations are generally valid when it comes to spurring the sustainable transition of the transport sector, the exact policy package should be evaluated for each case by taking the national, regional and urban contexts into account.

Concerning specific transport sub-sectors, in road transport, policies targeting heavy-duty vehicles still lag behind those targeting light-duty vehicles. Indeed, some regions (e.g. the European Union and the United States) have adopted fuel economy standards covering about half of the total heavy-duty market. However, such measures are still lacking in those countries where the activity from heavy-duty vehicles is expected to grow the most in the next decades [21]; rapid actions from these governments are therefore necessary. In aviation, international measures, such as progressively stringent carbon-pricing and efficiency standards, represent an action pivotal to containing the increase in emissions due to the rapid growth in activity [21]. In international shipping, the IMO has set the goal of reducing GHG emissions by 50% by 2050 compared with a 2008 baseline. However, because of the large price gap between conventional and sustainable technologies, mitigation measures stimulating strong efficiency enhancements and timely fuel-switching are crucial to achieving this goal. Lastly, stronger policy support and innovation to reduce the costs of low-carbon fuels, such as biofuels, are required for their widespread adoption, especially in aviation and maritime transport [21].

References

1. International Energy Agency (IEA). World Energy Outlook 2018. Paris, France: IEA Publications; 2018.
2. International Energy Agency (IEA). Energy Technology Perspectives 2016 - Towards Sustainable Urban Energy Systems [Internet]. Paris, France: IEA Publications; 2016. Available from: https://webstore.iea.org/download/direct/1057?fileName=Energy_Technology_Perspectives_2016.pdf
3. Center McKinsey For Business And Environment, C40. Focused acceleration: A strategic approach to climate action in cities to 2030 [Internet]. 2017. Available from: https://www.c40.org/researches/mckinsey-center-for-business-and-environment
4. International Energy Agency (IEA), Nordic Energy Research (NER). Nordic Energy Technology Perspectives 2016 [Internet]. Energy Technology Policy Division. Paris, France. Oslo, Norway: IEA; 2016. 269 p. Available from: http://www.nordicenergy.org/wp-content/uploads/2016/05/Nordic-Energy-Technology-Perspectives-2016.pdf
5. International Energy Agency (IEA). CO2 Emissions Statistics [Internet]. Available from: https://www.iea.org/statistics/co2emissions/ [accessed April 2019].
6. International Energy Agency (IEA), International Council on Clean Transportation (ICCT). Fuel Economy in Major Car Markets: Technology and Policy Drivers 2005-2017 [Internet]. Paris, France: IEA Publications; 2019. Available from: https://webstore.iea.org/download/direct/2458?fileName=Fuel_Economy_in_Major_Car_Markets.pdf
7. International Energy Agency (IEA), Nordic Energy Research (NER). Nordic EV Outlook 2018 - Insights from leaders in electric mobility. Paris, France: IEA Publications; 2018.
8. International Energy Agency (IEA). The Future of Trucks: Implications for energy and the environment. Paris, France: IEA Publications; 2017.
9. International Energy Agency (IEA). Digitalization & Energy [Internet]. Paris, France: IEA Publications; 2017. Available from: https://www.iea.org/publications/freepublications/publication/DigitalizationandEnergy3.pdf
10. United Nations Framework Convention on Climate Change (UNFCC). The Paris Agreement [Internet]. Available from: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement [accessed April 2019].
11. International Energy Agency (IEA). The Future of Rail: Opportunities for energy and the environment. Paris, France: IEA Publications; 2019.
12. International Transport Forum (ITF). ITF Transport Outlook 2017 [Internet]. Paris, France: OECD; 2017. (ITF Transport Outlook). Available from: https://www.oecd-ilibrary.org/transport/itf-transport-outlook-2017_9789282108000-en
13. International Energy Agency (IEA). Global EV Outlook 2019: Scaling-up the transition to electric mobility. Paris, France: IEA Publications; 2019.
14. International Energy Agency (IEA). Renewables 2018: Analysis and Forecasts to 2023. Paris, France: IEA Publications; 2018.
15. International Civil Aviation Organisation (ICAO). Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) [Internet]. 2019. Available from: https://www.icao.int/environmental-protection/CORSIA/Pages/default.aspx [accessed April 2019].
16. International Maritime Organization (IMO). UN body adopts climate change strategy for shipping [Internet]. Available from: http://www.imo.org/en/MediaCentre/PressBriefings/Pages/06GHGinitialstrategy.aspx [accessed April 2019].
17. International Maritime Organization (IMO). Energy Efficiency Measures [Internet]. Available from: http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Technical-and-Operational-Measures.aspx [accessed April 2019].
18. International Maritime Organization (IMO). Sulphur 2020: cutting sulphur oxide emissions [Internet]. Available from: http://www.imo.org/en/MediaCentre/HotTopics/Pages/Sulphur-2020.aspx [accessed April 2019].
19. International Energy Agency (IEA). Oil Market Report 2018. Paris, France: IEA Publications; 2018.
20. International Energy Agency (IEA). The Future of Hydrogen: seizing today's opportunities. Paris, France: IEA Publications; 2019.
21. International Energy Agency (IEA). Tracking Clean Energy Progress: Transport [Internet]. Available from: https://www.iea.org/tcep/transport/ [accessed April 2019].

Paper II

Energy Scenario Analysis for the Nordic Transport Sector: A Critical Review

energies

Review

Energy Scenario Analysis for the Nordic Transport Sector: A Critical Review

Raffaele Salvucci [1,*], Stefan Petrović [1], Kenneth Karlsson [1], Markus Wråke [2], Tanu Priya Uteng [3] and Olexandr Balyk [1]

[1] DTU Management, Technical University of Denmark, Produktionstorvet, Building 424, 2800 Kgs. Lyngby, Denmark; stpet@dtu.dk (S.P.); keka@dtu.dk (K.K.); obal@dtu.dk (O.B.)
[2] Energiforsk AB, Swedish Energy Research Centre, Olof Palmes gata 31, 101 53 Stockholm, Sweden; markus.wrake@energiforsk.se
[3] Institute of Transport Economics, Norwegian Centre for Transport Research (TØI), Gaustadalléen 21, 0349 Oslo, Norway; Tanu.PriyaUteng@toi.no
* Correspondence: rafs@dtu.dk; Tel.: +45-52634679

Received: 5 April 2019; Accepted: 6 June 2019; Published: 12 June 2019

Abstract: Experiencing the highest growth in emissions since 1990 and relying mainly on oil, transport is considered the most complicated sector to decarbonize. Lately, the Nordic countries have shown remarkable success in reducing greenhouse gas (GHG) emissions, especially in the power and heat sector. However, when it comes to transportation, the greatest source of Nordic GHG emissions, stronger measures are needed. Relying on a rich and diversified portfolio of renewable sources and expertise, the Nordic countries could benefit from a common mitigation strategy by encompassing a larger variety of solutions and potential synergies. This article reviews studies addressing integrated energy and transport scenario analysis for the Nordic region as a whole. The studies targeted are those applying energy system models, given their extensive adoption in supporting scenario analysis. Most notable of these studies is the "Nordic Energy Technology Perspectives 2016" to which a special focus is dedicated. The article reviews the methodological choices and the research content of the selected literature. Challenges/limitations are identified in light of recent transport research, and categorized as: "transport behavior", "breakthrough technologies", "domestic energy resources" and "geographical aggregation and system boundaries". Lastly, a list of suggestions to tackle the identified gaps is provided based on the existing literature.

Keywords: alternative fuels; decarbonization; energy system modelling; low-carbon transition; NETP 2016; sustainable mobility; transport behavior

1. Introduction

The transport sector is responsible for 23% of global greenhouse gas (GHG) emissions (2015 data), and it has the least diversified energy demand among all sectors, relying almost entirely on oil products [1]. In its baseline scenario outlined in the Energy Technology Perspectives (ETP), the International Energy Agency (IEA) estimates a 75% increase of global energy consumption in transportation by 2050 and a consequent doubling of associated CO_2 emissions [2]. Countries worldwide have already declared long-term mitigation measures in their National Determined Contributions. However, their commitments are still not in line with the Paris Agreement [3], which calls for more ambitious actions. In order to facilitate a transition to a low-carbon transportation sector, IEA suggests the adoption of a combination of three technological and behavioral measures: avoiding travel demand, modal shift and improvements in vehicle efficiency [4].

In the Nordic region, the transport sector represents the greatest source of GHGs. It accounts for almost 40% of total CO_2 emissions, which is higher than the global average. However, the Nordic countries are pioneers in deploying sustainable energy technologies, each with its peculiarities: e.g. wind power in Denmark, hydropower in Norway, biomass in Finland and Sweden and geothermal energy in Iceland. Moreover, the well-integrated Nordic regional electricity market is enabling a high penetration of renewables, for instance connecting Norwegian hydro reservoirs to Danish wind farms in periods with a lack of demand. Besides the power and heat sector, the Nordic transport sector has also started a slow sustainable transition. For instance, the aggressive policy support for electric cars (especially in Norway) has recently made the Nordic region the third largest electric car market by volume of sales in the world, just after China and the United States [5]. However, the Nordic transport sector is still far from decarbonization.

Relying on a rich portfolio of diversified renewable energy sources and expertise, Nordic countries could benefit by outlining a common Nordic mitigation strategy by encompassing a larger variety of sustainable solutions and possible synergies [6]. Moreover, the Nordic region is already today in a favorable position in creating first-mover advantages regarding the low-carbon technological transition [7]. Therefore, besides benefitting from reducing their own emissions, the Nordics could eventually help other European countries in achieving their environmental goals by exporting the developed solutions and expertise.

Energy system models have been supporting long-term decision making for the energy sector for long time and for different countries [8], representing valuable and powerful tools for identifying specific technology deployment pathways under alternative policy scenarios. Energy system analysis has been extensively applied also to investigate dedicated decarbonization strategies for specific sectors such as heat [9], residential [10] and transport [11,12]. However, despite the potential benefits in outlining a common Nordic strategy, most of the available literature focuses on single countries, e.g. Denmark [11,13], Iceland [14], Norway [15] and Sweden [12], while the Nordic region as a whole is addressed only by few studies, calling for further analyses.

The aim of this article is to review the state of the art of studies applying energy system analysis for integrated energy and transport scenarios for the Nordic region, and to provide recommendations for future research. Specifically, the studies targeted are those addressing the Nordic region as a whole, enabling the identification of possible synergies across countries, thus studies focusing on single Nordic countries are not reviewed. The identified literature is analyzed in terms of methodological choices adopted and research content targeted. Among all the studies reviewed, a special focus is given to the "Nordic Energy Technology Perspectives 2016" (NETP 2016) [16], which, despite being published three years ago, still represents the most complete study assessing future energy scenarios for the Nordic region. Based on the critical review of the selected literature, research gaps are identified and discussed in light of recent findings in transport research. In particular, the gaps are organized in four main categories: 1) transport behavior, 2) breakthrough technologies, 3) domestic energy resources and 4) geographical aggregation and system boundaries. A list of solutions to tackle the identified gaps is provided based on additional literature including also single Nordic country analyses.

In Section 2, the criteria adopted for the review are provided. In Section 3, the results of the review are presented. Section 4 identifies the research gaps and discusses the motivation to fill them. Moreover, a set of best practice examples is provided based on additional relevant literature, and insights on the implications of adopting such practices are discussed within an energy system modelling rationale. Finally, Section 5 articulates the conclusions.

2. Review Methodology

The Nordic countries are in a favorable position in deploying a common long-term strategy for a sustainable future transport sector. Indeed, the synergic exploitation of national energy sources, technology expertise and infrastructure could facilitate such low-carbon transition. In light of the above, the focus of this review is on studies addressing long-term energy scenario analysis for a low-carbon Nordic transport sector, applying energy system modelling. In particular, energy system analysis represents a well-established scientific discipline that has been extensively used for decades to support future scenario analyses. Moreover, the geographical scope of the review is the Nordic region as a whole; therefore, studies focusing on a single Nordic country are omitted. However, some of them are discussed together with additional relevant literature in Section 4. The aim of the article is to provide an up-to-date overview of existing literature on the topic, identify limitations and research gaps and propose suggestions for future studies targeting the same research area.

The review was carried out during March 2019 through three main steps. First, an automatic literature search of journal articles was performed through online academic databases, namely, Web of Science [17], DTU Findit [18] and Scopus [19]. Then a manual screening was executed to filter out irrelevant studies. Lastly, the assembled literature was integrated with additional relevant reports and book chapters selected manually based on the authors' knowledge.

Concerning the automatic database screening, the string adopted for the search was formulated as follows: (transport* OR "transport system" OR "transport sector") AND (scenario*) AND (energy system* OR "energy system analysis") AND (Nordic* OR Scandinavia* OR "Northern Europe"). The search was performed for the *topic* field in Web of Science, *All fields* in DTU Findit and *Title, abstract and key words* in Scopus. The search led to a total of 95 hits, which has been progressively reduced to 8 after including only works in English, removing duplicates and excluding irrelevant research areas and journals. In addition, studies with a focus on only a single Nordic country were omitted. The manual screening was carried out first by title and then by reading the abstract and, eventually, if necessary, the full article.

In Section 3.1, the identified studies are commented based on their specific research questions and the methodology applied. A special focus is given to the NETP 2016 [16], which stands as the most complete study assessing future energy scenarios for the Nordic region. The NETP 2016 results are analyzed with a particular focus on the transport sector analysis, and in terms of methodological tools and modelling choices (Section 3.2). The NETP 2016 review is based on publicly available reports and data (accessible at [20]), as well as on more detailed model results provided by IEA and Nordic Energy Research (NER), and on personal communications with scientists involved.

3. Results

Section 3.1 presents the results of the literature review, while Section 3.2 describes in details the NETP 2016 methodological approach and results.

3.1. Nordic Transport Energy Scenarios

There are several studies investigating long-term energy scenarios for a low-carbon Nordic transport sector, which address specific research questions from different perspectives. In this study, the focus is on works applying energy system analysis as methodological tool, and addressing the Nordic region as a whole. Usually, the research questions targeted, in the identified articles, involve the investigation of the potential role of a specific transport technology in the decarbonization of the Nordic transport sector. The adoption of specific technologies is analyzed in terms of effect on the overall energy system or part of it. Broadly speaking, the most common technologies investigated are electric vehicles (EVs), and the adoption of first- and second-generation biofuels and hydrogen as alternative transport fuels.

The effect of a high penetration of EVs in the Nordic energy system is the most investigated topic, which is usually addressed via optimization and linear programming. In particular, the effect of different charging scenarios on the day-ahead energy planning and on the yearly electricity demand and transmission requirements up to 2050 are analyzed in [21] and [22], respectively. Other studies focus on the role of EVs for a future low-carbon road transportation in the Northern European area (Scandinavia and Germany). Reference [23] applies the Balmorel energy system model up to 2030 to investigate the effect EVs on the power system, while [24] studies the impact of EVs on the electricity generation capacity and dispatch, including the use of electrified roads for trucks and buses. Additional information on Balmorel can be found in [25].

Concerning biofuels, the deployment of forest-based (second generation) biofuels as a long-term mitigation strategy to decarbonize the Fenno-Scandinavian (Norway, Finland and Sweden) road transport sector is addressed in [26] applying an input-output model. The analysis investigates the production of biofuels and their consumption in the transport sector under different assumptions including future technology deployments and demand projections up to 2050. However, most of the studies dealing with energy scenarios for biofuels are country specific, e.g. [27] and [12]. Since the scope of this review is the Nordic region, national studies are omitted.

The role of hydrogen in the transition towards a 100% renewable Northern European energy system is investigated by [28]. In particular, Balmorel is applied to study the effect of hydrogen penetration in the power, heat and transport sector up to 2060. A similar study [29] estimates, via simulation, the effect of hydrogen and biofuels penetration in the transport sector on the Northern European power sector for the year 2060. Reference [30] analyzes the technical and economic potential of different hydrogen technologies (production and consumption) in the Nordic region. Namely, a linear-programing, technology-based hydrogen energy model is applied under different assumptions regarding fossil fuel prices, technology costs and hydrogen demands to investigate the role of hydrogen in the Nordics until 2030.

Lastly, besides the energy system modelling approach, some studies analyze the long-term decarbonization of the Nordic transport sector from other perspectives. For instance, ref. [31] analyzes three technology platform value chains for a sustainable Nordic road transport, namely e-mobility, hydrogen fuel cell vehicles and advanced liquid and gaseous biofuels. However, such works are out of the scope of this review.

Only few of the identified studies address the research question of how to achieve a low-carbon transport sector taking into account the entire Nordic energy system. These studies go beyond the sole interaction between, e.g. the power and transport sectors, but they explicitly account for all the other sectors (from the supply to, e.g. industry and households). Such studies provide a more comprehensive analysis of how to achieve a low-carbon Nordic energy system while providing sector specific insights including dedicated transport analysis. For instance, [32] applies a TIMES (The Integrated MARKAL-EFOM System) model of the Scandinavian energy system to investigate pathways towards carbon neutrality by 2050. The transport sector is analyzed under a "no import of biofuels" assumption and a low electrification of heavy duty vehicles, resulting in hydrogen as the dominant fuel. Furthermore, [33] analyzes how to achieve a 100% renewable share of primary energy supply in the Nordics by 2050 applying TIMES-VTT, a full energy system model of Denmark, Finland, Norway and Sweden. The study investigates the role of power-to-gas technologies under different assumptions involving the availability of forest biomass for energy use and the penetration of biofuels and hydrogen in the transport sector. More information on TIMES models are provided by [34].

To summarize, all the mentioned studies analyze long-term low-carbon energy scenarios for the Nordic transport sector. They address specific research questions, which are usually centered around a single or limited set of technologies. The integration of the studied technologies is usually investigated with respect to only a part of the energy system, for instance, the power sector. Only a few studies include the whole energy system [32,33]. The inclusion of the whole energy system in the analysis allows the identification of synergies between technologies and of resource competition across sectors while fulfilling common environmental targets. Lastly, most of the identified studies focus only on road transportation, while either neglecting the rest of the transport sector or including it partially.

To the authors' best knowledge, despite the fact a few years have elapsed since its original publication, the most comprehensive study addressing long-term energy scenarios for a low-carbon Nordic transport sector is the NETP 2016 [16], the second of this series. In this series of studies, the modelling framework includes the whole Nordic energy system. This enables the investigation of cross-sectorial and cross-country solutions and resource allocation, while providing insights on the possible role of specific transport technologies in the decarbonization of the Nordic transport sector (including rail, navigation and aviation). The NETP 2016 strives for ambitious goals while adopting a quantitative approach. It relies on a solid modelling framework from the ETP studies, which results in a well-documented and integrated analysis. NETP studies represent a benchmark within the energy arena, as witnessed by the numerous articles referring to the NETP 2016 results. Few examples are given by [35], which comments upon the NETP 2016 results from a social and political point of view, while [32] refers to the NETP 2016 findings for comparisons. For this reason, Section 3.2 thoroughly reviews the NETP 2016, focusing on the findings for the sole transport sector. Moreover, the NETP 2013 study is not reviewed, since the findings of NETP 2016 are directly built upon it.

Lastly, the Nordic region is also addressed by studies targeting integrated energy and transport scenario analysis for larger geographical areas, such as the European [36] or even the global one [37]. However, given the relative size of Nordic countries on the European and global scale, these studies usually pose little focus on the Nordic region compared to dedicated Nordic studies; hence, they are not part of this review.

3.2. NETP 2016

NETP 2016 follows the principles of the ETP series of studies by IEA [16], whose aim is to identify sustainable energy technology transition pathways, globally and for specific regions. The ETP-TIMES model represents the backbone of the approach. It is a cost driven bottom-up optimization model including the five Nordic countries (Denmark, Finland, Iceland, Norway and Sweden) as separate model regions. ETP-TIMES represents the Nordic energy conversion sectors (electricity generation, refineries, etc.) and is soft-linked to three end-use sector models (namely industry, buildings and transport), utilized to derive projections of final energy demands. ETP-TIMES identifies the least-cost technology mix to meet the final energy demands for the whole time horizon under several constraints mirroring the different scenario assumptions ([16], p. 221). These constraints range from feasible renewable energy potentials and CO_2 prices to policy instruments [38]. Two additional tools support ETP-TIMES. A linear dispatch model analyzes the operation of the electricity sector and assesses the need for flexible generation and storage in the energy system obtained from the ETP-TIMES model. Besides, the Balmorel model investigates the electricity trades and transmission expansions within the Nordic region and towards Europe ([16], p. 222).

Among the end-use sector models, the transport sector is represented by the Mobility Model (MoMo) developed by IEA [39]. MoMo is a techno-economic spreadsheet and simulation model capable of making detailed projections of transport and vehicle activity, energy demand, direct and well-to-wheel (WTW) GHG and pollutant emissions ([16], p. 224). Population and gross domestic product (GDP) projections together with private vehicle ownership rates are key drivers to calculate the service demand, or alternatively, the vehicle demand, depending on the mode [40]. Modal shares and average efficiency improvements for different technologies are exogenously estimated by experts [41]. Energy consumption and emissions are calculated based on the ASIF identity [42].

The whole NETP 2016 analytical framework refers to an urban and a non-urban dimension. Due to the lack of a common definition of urban areas, the respective national definitions were adopted for each country. The urban/non-urban disaggregation in NETP 2016 is achieved as in ETP 2016. This process involves a number of assumptions and regression analysis to fill the data gaps ([1], p. 144) (Appendix A.1).

NETP 2016 focuses on a central scenario, the Carbon Neutral Scenario (CNS), where Nordic energy related CO_2 emissions drop by 85% by 2050 compared to 2013 levels. The less ambitious Nordic 4 Degree Scenario (4DS) is also included. It reflects the Nordic contribution to the IEA's global 4DS ([16], p. 35), where the global increase in GHG emissions is limited to 20% relative to 2013 levels ([1], p. 32). The CNS and 4DS are the results of a mix of scenario types, back-casting and forecasting ([16], p. 219). This scenario approach is applied in different ways. ETP-TIMES uses an optimization algorithm, while MoMo outlines a solution through simulation, which is guided by manual iterated adjustments to mirror what experts believe to happen given a specific set of assumptions. The procedure consists of supplying the projected transport demands, given a set of technological options and a specific carbon budget. The priority is given to energy efficiency improvements and to the deployment of cheaper sustainable solutions (given the different technology cost curves). Finally, the penetration of expensive technologies are allowed if part of the demand is still uncovered [43]. For instance, in aviation, due to the future demand growth, efficiency maximization and fuel shift towards biofuels were insufficient to keep the emissions below the carbon budget. Therefore, a shift towards high-speed rail (expensive technology) was necessary to be included in the CNS [43]. For more information regarding the NETP 2016 scenario building process, refer to Appendix A.2.

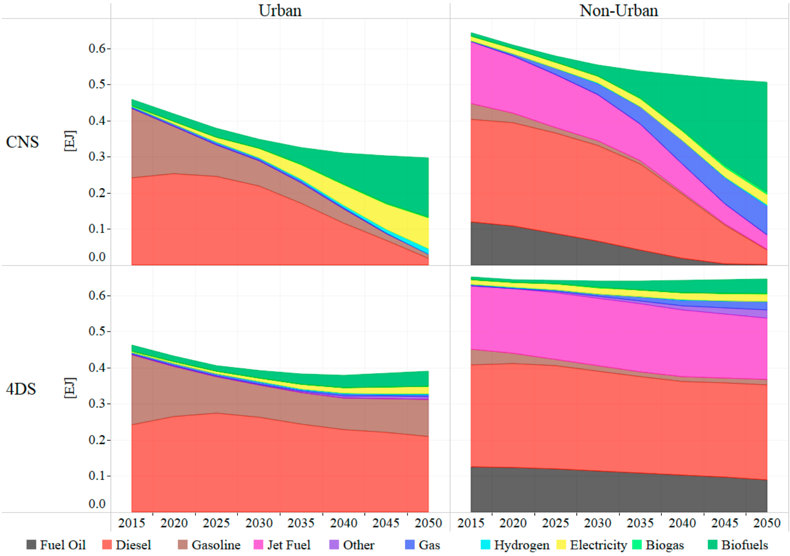


Figure 1. Nordic transport final energy demand (EJ) in urban and non-urban areas. Including international aviation and shipping, excluding pipeline transport. Results from MoMo, provided by [44], are interpolated with a five-year step resolution. "Biofuels" includes ethanol, biodiesel, bio oil, and bio jet fuel, while "Other" includes gas- and coal-to-liquid fuels.

Concerning the NETP 2016 results, from 2015 to 2030, the CNS and 4DS have similar final energy demands (Figure 1). In the following period, the CNS is more ambitious, requiring considerable improvements in vehicles fuel economy ([16], p. 66), and a higher penetration of renewable fuels. In the CNS, by 2050, transport final energy demand drops by 20% compared to 2000 levels, reaching 0.87 EJ despite a 70% increase in total transport activity. This happens due to energy savings (especially among cars), but also to modal shift towards more efficient modes and slightly to non-motorized modes in urban areas ([16], p. 123). For instance, high-speed rail covers 13% of the growing aviation transport demand ([16], p. 70). In 2050, fossil fuels account only for 25% of final energy use, biofuels represent the highest consumption category with 60% (around 0.48 EJ), while electricity represents slightly more than 10%. Biofuel vehicles cover mainly long distance, heavy duty road and marine freight and aviation transport demands. On the other hand, electric vehicles cover light and mid duty freight and short distance passenger trips, especially in urban areas. Powertrains have higher efficiencies than internal combustion engines (ICEs), resulting in lower energy consumption. Indeed, electric vehicles, including battery electric (BE), plug-in hybrids and hybrids, represent 78% of the stock in 2050, followed by fossil fuel ICE vehicles (21%) and fuel cell (FC) electric vehicles (1.4%). In particular, hybrids dominate among trucks operating in non-urban areas with 62% of the stock, followed by diesel ICE vehicles (22%). Lowering emissions in the transport sector would require a tight cooperation among Nordic countries. The broad electrification of urban transport in the CNS is based on a synergistic coordination to integrate and decarbonize the Nordic electricity market. The high penetration of wind power relies on more active use of Norwegian and Swedish hydropower through a highly interconnected power system. The deployment of high-speed rail would require the development of an infrastructure network linking Nordic capitals. Lastly, the large import of biofuels calls for a joint Nordic collaboration to research and develop advanced biofuels and a strategy to efficiently utilize the Nordic biomass across regions and sectors.

Within the 4DS, in 2050 transport final energy demand stabilizes at 1.10 EJ (Figure 1), thanks to efficiency improvements in passenger light duty vehicles (LDVs) and a moderate deployment of hybrids, though, 88% of final energy demand in 2050 is still supplied by fossil fuels, followed by biofuels (8%) and electricity (4%). Fossil ICE vehicles represent 60% of the stock followed by hybrids (27%), while the rest is shared among BE and FC electric vehicles.

In the CNS, WTW GHG emissions face a 70–80% reduction compared to 2015 levels (Figure 2). Tank-to-wheel (TTW) GHG emissions drop by 40% within the same period. This is also possible thanks to the almost fully decarbonized Nordic electricity system in 2050. In the 4DS, transport activities in 2050 account for 10% lower WTW GHG emissions than 2015 levels ([16], pp. 71).

Figure 2. Well-to-wheel (WTW) and tank-to-wheel (TTW) GHG emissions in the CNS and 4DS. Results from MoMo, provided by [44], are interpolated with a five-year step resolution.

4. Discussion—Identified Challenges and Recommendations

In light of the literature review, some recommendations are drawn for future long-term energy scenario analysis for a low-carbon Nordic transport sector. In particular, challenges and gaps are identified in the reviewed literature based on recent findings in transport research tackling sustainable mobility. The identified gaps are categorized as: "Transport behavior", "Breakthrough technologies", "Domestic energy resources" and "Geographical aggregation and system boundaries". Recommendations to overcome the identified gaps are based on forefront studies targeting long-term energy scenario analysis for the transport sector but including other geographical scopes than the reviewed one. Table 1 summarizes the studies identified by the authors, which tackle the identified gaps in their methodological framework. Each of the examples is commented in terms of effects/repercussions on the scenario analysis within an energy system modelling rationale.

Table 1. Examples of studies tackling the identified challenges in their works.

Challenges	Solution Examples
Transport behavior	
Modal competition	[11,45–49]
Autonomous vehicles and MaaS	-
Breakthrough technologies	
Electrified roads	[50]
Fuel cell and battery electric trucks	[51–54]
Electric ferries	-
Carbon capture and storage	[55–58]
Domestic energy resources	
Biofuels—2nd generation	[12]
Electrofuels	[59]
Geographical aggregation and system boundaries	
Urban dimension	[47]

The following sub-sections discuss separately the identified gaps by introducing motivation, discussion and recommendations.

4.1. Transport Behavior

As pointed by [60], the behavioral dimension is crucial when investigating mitigation solutions for transport energy-related CO_2 emissions. However, energy-economy-environmental-engineering (E4) models are still weak at simulating behavioral changes. There have been some attempts to fill this gap by incorporating behavioral features in integrated energy and transport models [61]. However, these attempts do not appear in most of the reviewed Nordic studies. The NETP 2016 represents an exception; behavioral aspects are included in MoMo. In particular, vehicle ownership rates are mapped with respect to income and GDP per capita applying Gompertz type curves, while mileage is mapped with respect to income and fuel prices. In ambitious scenarios, where policies promoting modal shift are put in practice in a specific country, the reduction in car ownership is obtained by moving to a lower Gompertz curve based on what observed in other countries in the past. However, emerging phenomena deeply dependent on the behavioral dimension, such as autonomous vehicles, car-sharing, car-pooling and in general mobility as a service (MaaS) are only indirectly considered when estimating car ownership reduction and efficiency increase potentials (due to more efficient driving patterns) ([16], p. 120). The direct inclusion of the behavioral dimension in E4 models could enable the investigation of behavioral change policies. This is particularly relevant when new mobility trends are integrated in the analysis as it gives the possibility to assess effective policies promoting the adoptions of such measures. Moreover, non-motorized modes are not directly modelled in MoMo, though they are considered when estimating passenger transport activity in urban areas. The explicit modelling of such modes could allow analyses of interactions between them and public transport or, potentially, MaaS in terms of complementarity or synergies as underlined by [62].

As presented in [61], the inclusion of behavior into integrated energy and transport models recognize two main approaches. The first involves linking the E4 model with an external transport model incorporating the behavioral dimension. The second approach consists of broadening the E4 classical framework to integrate some transport specific variables/dimensions to emulate transport behavior in order to estimate endogenously, for example, modal choice or shift. NETP 2016 can be roughly categorized in the first group. The remaining studies reviewed include E4 models with an aggregated/partial representation of the transport sector, where behavior is not endogenously modelled.

Concerning the second approach, there are several methods to include behavior in E4 models. For instance, [11,45,46] emulate modal shift by integrating the concept of travel time budget and transport infrastructure, [47,48] introduce endogenous modal choice through modelling modal level of service and consumers' decisions, while [49] adopts substitution elasticities to enable modal shift. These approaches include different levels of transport behavior in E4 models and thus offer different capabilities, and require different data sources. Therefore, such methodological adoption is dependent on the specific research question addressed by practitioners. However, enhancing the capability of E4 models to capture behavior dynamics when investigating policies, represents a desirable improvement when tackling transport energy scenarios. For instance, the mentioned methodologies are capable of enabling endogenous modal shift, one of the pivotal measures identified by the IEA and the European Commission [4,63,64] for a low-carbon passenger and freight transport sector. In addition, emerging phenomena largely affected by behavior such MaaS (including car-sharing and car-pooling) and autonomous vehicles could be investigated in a more direct way. Indeed, autonomous vehicles could reduce congestion and car ownership and increase mileage (more efficient use of the fleet), especially if coming along with car sharing and pooling, and provide electricity storage in the case of electric vehicles [65]. Nevertheless, if wrong policies are in place, they could instead increase congestion and transport activity. However, no studies including explicitly these emerging mobility phenomena in energy system models were found by the authors.

4.2. Breakthrough Technologies

Lately, innovation in transport technologies has gained strong momentum. Therefore, the inclusion of up-to-date breakthrough technologies in the modelling framework is challenged by the continuous innovation pace. However, some emerging technologies particularly interesting for the Nordic case can be identified.

In the NETP 2016, electrified roads and fuel cell trucks are identified to have the potential of suppling part of the long distance road freight transportation ([16], p. 21). Despite this, electrified roads are excluded from the analysis, while fuel cell trucks are only partially included due to their technical and economic uncertainty. The authors recognize the benefit in outlining a scenario demonstrating that policy targets can be achieved with well-known and available technologies. However, the NETP 2016 could have employed less probable and innovation rich scenarios (also known as "wild cards" or "black swans") to test the response of the system under circumstances "beyond the expectations", as recognized by [35]. The inclusion of electrified roads in the analysis represents a desirable improvement, especially considering that electric and hybrid vehicles are highly deployed within the NETP 2016 scenarios, for both LDVs and trucks (Section 3.2). In addition, pilot projects assessing their technical and economic feasibility are ongoing in Sweden, Germany and USA [66], which can provide preliminary figures. Moreover, a high deployment of hydrogen long haul trucks and battery powered regional trucks could be interesting, especially when considering limited bioenergy resources [32].

Electric ferries represent another interesting technology that can support a low-carbon transport sector in the Nordics. In MoMo, shipping includes only freight transportation while maritime passenger transport is not directly included. The reason behind such modelling architecture is that the biggest shipping energy demand worldwide resides in the freight sector. However, maritime passenger transportation causes roughly a quarter of total shipping emissions taking place in the Nordic waters, namely 6.5 Mtonnes of annual CO_2 emissions [67]. In particular, electric ferries are under development by different companies in the Nordics [68]. Moreover, "green" coastal shipping is compliant with one of the main barrier to expand coastal shipping, which is coastal air quality, therefore, it represents also an attractive alternative for the growing freight road transportation.

Summarizing, electrified roads, FC and BE trucks and electric ferries represent potential breakthrough technologies for the Nordic region. The inclusion of these technologies in the scenario analysis would enable the assessment of the impacts of hydrogen and electricity demands on the whole energy system. This is particularly important in the Nordics, where the electricity system is already accommodating large amounts of intermittent sources (e.g. wind power), and thus hydrogen production and electricity smart charging could represent additional flexibility sources [28]. Considering the available literature, some studies analyze the effect of electrified roads on the power system through the representation of their electricity demand as done by [24]. To the authors' knowledge, the only study including explicitly such technology in an E4 model is represented by [50]. This study evaluates the economic viability of electrified roads in the decarbonization of the Danish transport sector. An explicit inclusion of hydrogen long haul trucks and battery powered trucks appear in more studies, addressing, for instance, energy scenarios for South Africa [51], Japan [53,54] and even globally [52]. Lastly, no studies including electric ferries in energy system models are available.

Another interesting emerging technology is carbon capture and storage (CCS). In the Nordics, the adoption of CCS is particularly interesting for emissions reduction in the heavy industries [69]. This is reflected in the NETP 2016 CNS, where a wide adoption of CCS accounts cumulatively for almost 30% of total direct industrial CO_2 emissions reduction over the period 2020–2050 [16] (p. 24). Even though CCS cannot be directly applied in the transport sector, its inclusion in the analysis is interesting when looking at dedicated scenarios for the sole transport sector. In particular, when the full energy system is described in the modelling platform, and a common environmental goal is set up (such as a carbon budget), CCS technologies can provide flexibility in reducing emissions across the sectors. For instance, CCS can free biomass feedstocks for biofuels production in sectors where alternative solutions are limited (such as aviation or heavy industries [27]). Moreover, the development of bio-energy with carbon capture storage (BECCS) technologies has recently grown in interest in the Nordic countries [70], given their tradition in heat and power generation from biomass and the large potential for feedstocks. BECCS technologies could be employed to obtain negative emission "credits" from the combustion of biomass to be spent in other sectors.

The inclusion of CCS technologies as a mitigation option in E4 models is nowadays nearly a common practice, e.g., [55–58]. Including an up-to-date CCS technology portfolio in the analysis of low-carbon energy scenarios for the transportation sector, could provide additional cross-sectorial solutions for transport modes whose emissions are harder to reduce (e.g. aviation). This is particularly relevant in a region with large CO_2 storage potential, such as the Nordic one [71].

4.3. Domestic Energy Resources

The use of bioenergy as a mitigation measure represents a controversial topic. In the CNS, the Nordic region becomes a net importer of bioenergy, by increasing net biofuel imports four times to meet the growing demand in transport, which in 2050 represents two thirds of total final energy use (0.48 EJ, Figure 1). This vision is contextualized within a carbon constrained global context where, most likely, the demand for bioenergy will increase as well. Decarbonizing the Nordic transport sector relying heavily on biofuels imports could be questionable in terms of sustainability; therefore, [32] includes a scenario where bioenergy imports to the Scandinavian region are excluded. The authors recommend following a similar approach when investigating sustainable pathways for the Nordic region, to challenge the studied scenarios with net zero bioenergy imports and to investigate an efficient strategy to allocate domestic biomass feedstocks across the sectors. Furthermore, there are several promising emerging biofuel conversion pathways (mostly forest-based or second-generation) [72], whose inclusion in energy system models is growing in interest, as shown by [73]. Concerning the independence from alternative fuels imports, electrofuels represent also a promising option for transportation to include in the scenarios [74]. Besides providing an alternative to fossil fuels, also in those cases where solutions are limited (such as aviation) [75], electrofuels offer energy storage capability for intermittent renewables, as wind and photovoltaics.

Given the high potential for domestic biofuel production in the Nordics [76], an up-to-date bio-refinery technology portfolio is recommended to be included in the analysis, as done, for example, by [12] in the MARKAL_Sweden model. The same applies for electrofuels, whose role in decarbonizing the Nordic transport sector could be investigated quantitatively by including them in the modelling framework, as done by [59] in the JRC-EU-TIMES model. Lastly, hydrogen, besides being used in the electrofuel production, represents a potential alternative transport fuel itself, whose production technologies should also be included, as often done, in E4 models, such as by [77]. Implementing an exhaustive representation of alternative fuel production chains in energy system models provides two main benefits. First, it sheds lights on the optimal use of domestic energy resources. Secondly, in the case of hydrogen and electrofuels, it provides insights on energy storage capabilities in a system with high penetration of variable renewables, such as the Nordic.

4.4. Geographical Aggregation and System Boundaries

Due to the increasing urbanization and its potential for deploying specific sustainable mobility solutions, the urban area is often mentioned as an increasingly important dimension when analyzing the future of mobility [16] (see Appendix A.1). In particular, Nordic capitals are already global leaders in sustainable transportation (Copenhagen's bike lanes, Oslo's electromobility, Stockholm's public transport) ([16], p. 108) and thus represent cutting-edge case studies. Moreover, urban planning influences considerably transport behavior, not just driving patterns but also modal choice [78]. Therefore, urban planning represents itself a long-term policy instrument for energy demand reduction, which should be integrated in the scenario discussion [79]. However, the urban dimension is neglected in the modelling framework for most of the reviewed studies. The NETP 2016 represents an exception, where, for the first time within the ETPs, the urban dimension is analyzed with special focus and dedicated tools.

The authors encourage practitioners to capture the urban dimension in their integrated energy and transport analyses to depict the great potentials of cities in deploying effective mitigation measures, particularly for the Nordic case. This is especially true for long-term scenario analysis, where the slow changes in the urban structure, which usually involve a long time span, become feasible and open for policy discussion. Several energy system models have been developed for specific cities to support integrated energy and transport analysis such as for Malmø [80], Oslo [81] and the Helsinki region ([16], p. 232). Other studies differentiate between urban and non-urban transportation in national E4 models. One example is given by [47], which provides a modelling design characterizing transportation across the urban, suburban and rural areas for Denmark.

In addition, when investigating energy pathways for a low-carbon transportation sector in the Nordic countries, addressing these countries as parts of a unique system can shed lights on additional solutions by encompassing more options and synergies. However, it is crucial to keep a detailed description of the individual countries, given their differences in, e.g. the geography, resources availability and travel habits, which result in heterogeneous transport challenges [82]. This is done for example by [32,33]. Instead, in the NETP 2016, Nordic countries in MoMo are aggregated into two regions: "EU Nordic" (Denmark, Finland and Sweden) and "Non EU Nordic" (Iceland and Norway). The split of results at a country level is achieved with approximate methods mainly based on population [43]. The lack of a Nordic country subdivision in MoMo, is due to its application in the wider focus of the ETP studies. Thus, efforts enhancing the level of details have been directed towards those regions where emissions and energy demands are dominant in a global context. The authors suggest depicting single country description in the modelling framework even when addressing the Nordic region as a whole. This enables to identify synergies across countries when pursuing a common goal while suggesting country specific strategies and policies in light of national resources and major differences in the energy and transport systems.

A similar suggestion can be drafted for the energy system depicted by the modelling platform. Indeed, including all sectors of the energy system in the analysis, as done by [16,32,33], can shed lights on resource competition and technological synergies across sectors when fulfilling common environmental targets, such as the exploitation of waste heat from bio refineries as heating source.

In addition, in ETP-TIMES, each Nordic country is modelled as a single region since the ETP 2013 study. In the NETP 2016, the electricity trade across the different power regions is assessed with the support of the Balmorel model. An interesting improvement could be to model the power regions inside the main modelling framework, as done by [32], allowing interregional trade of electricity and, potentially, of other commodities (e.g. domestic biomass or hydrogen), resulting in a fully integrated tool. This is especially relevant considering all the above suggestions, involving the inclusion of different energy carriers and their production chains. Moreover, with the exception of the NETP 2016, in most of the reviewed studies, international shipping and aviation are not part of the analysis. However, effective strategies for reducing emissions in such sub-sectors will also be needed; therefore, their inclusion in the analysis is necessary for a more exhaustive outlook.

Lastly, in the CNS, WTW emissions were claimed to drop by 70–80% in 2050 compared to 2015 levels (Figure 2). In particular, well-to-tank (WTT) emissions contribute largely to the overall reduction (Section 3.2). The GHG balance of fuel pathways production assumed for the WTT emissions calculations are retrieved from the Joint Research Centre (JRC) life-cycle assessment (LCA) study [83,84]. Such study adopts a system expansion approach to account for co-products obtained in the fuel production pathways (incremental approach). Emissions avoided due to co-products substitution are considered in the GHG balance as emission credits. The identification of such co-products depends strongly on the system boundaries and methodological assumptions defined within the LCA goal and scope, which, in this case, has a European focus. This assumption implies that transport fuel production chains are assumed located in a generic European context. This has specific repercussions on the emissions calculations. For example, in the case of electricity substitution, emissions savings are higher in a European context compared to the Nordic one, due to a higher carbon content. Even though the CNS relies heavily on biofuels imports, their future provenience is uncertain. A remarkable portion of the claimed reduction in the transport GHG emissions is based on figures valid within the goal and scope of the LCA study, which are different from the NETP 2016, undermining the solidity of the obtained results. Moreover, the avoided emissions for fuel production pathways are not accounted for other sectors. A more solid and consistent approach for GHG emissions accounting across the whole analytical framework is desired. The authors encourage the accounting of WTT emissions as long as they are consistently integrated in the analysis framework. For instance, they could be directly calculated by including fuel production chains in the modelling platform as suggested above.

Moreover, the inclusion of non-CO_2 emissions in the modelling framework is a good practice. In fact, the use of alternative fuels in the transport sector could bring some surprises if other GHGs besides CO_2 are left unchecked. For instance, incomplete methane combustion in ICEs or leakages from pipelines could represent a possible issue, given its larger global warming potential compared to carbon dioxide [85].

Lastly, except for the urban dimension, the authors do not provide examples to tackle the rest of the suggestions since they represent only modelling choices and do not involve any novelty.

5. Conclusions

This article reviews the state of the art of studies applying energy system analysis for integrated energy and transport scenarios for the Nordic region. The identified studies are reviewed in terms of methodological choices and research content. A special focus is posed on the NETP 2016, which stands as one of the most complete analysis of future energy scenarios for the Nordic region. Based on the systematic and critical review, challenges and solutions are identified for the following categories: 1) transport behavior, 2) breakthrough technologies, 3) domestic energy resources and 4) geographical aggregation and system boundaries.

The inclusion of transport behavior into the modelling framework, enabling, for example, endogenous modal shift, is a desirable improvement. In addition, capturing transport behavioral change could allow detailed analysis of emerging mobility trends such as autonomous vehicles and MaaS, whose direct inclusion is also identified as a potential improvement.

The inclusion of breakthrough technologies, such as electrified roads, FC and BE trucks, and electric ferries in energy system models is particularly interesting for the Nordic case. These technologies could rely on an almost decarbonized power sector and potentially provide demand side flexibility to a system with a large amount of intermittent renewables. Besides, the inclusion of CCS technologies could provide additional (cross-sectorial) solutions for those transport modes whose emissions are harder to reduce (e.g. aviation). However, the inclusion of CCS in energy system models is almost a common practice.

A sustainable use of biomass represents another important challenge, particularly relevant in a future carbon constrained world. Therefore, the authors recommend the inclusion of up-to-date second-generation biofuel conversion and electrofuel production technologies to investigate domestic alternatives to large biofuels import.

Due to the growing urbanization and the great potential that cities have in deploying green mobility solutions, we recommend depicting the urban dimension in the modelling platform. At the same time, we suggest to keep a distinctive representation of single countries to capture national resources and peculiarities, such as travel habits and geographic features. In addition, an explicit representation of the power regions (bidding areas) is particularly relevant considering the potential role of electricity in the future Nordic transportation, while including the full energy system could provide insights on cross-sectorial solutions. Besides, the full transport sector, including international shipping and aviation, should be addressed when analyzing the Nordic emission reduction strategies. Lastly, modelling other GHGs besides CO_2 is recommended, together with consistently integrated WTT calculations.

For each of the identified challenges, we have provided recommendations to tackle them based on the existing literature. However, in some specific cases, such as electric ferries, MaaS (including car-sharing and car-pooling) and autonomous vehicles, no previous studies were found. These challenges represent opportunities for further research. Finally, some of the improvements suggested (such those relative to alternative energy carriers and CCS) are also valid outside the narrow paradigm of integrated energy and transport analysis.

Author Contributions: R.S. performed the review and wrote the manuscript. S.P., K.K., M.W., T.P.U. and O.B. revised the manuscript and provided important recommendations. In particular, K.K., M.W. and O.B. helped with analyzing the modelling framework adopted in the NETP 2016 project. T.P.U. provided support on commenting upon the NETP 2016 transport scenarios analyses. All authors read and approved the final manuscript.

Funding: This research was part of the Nordic Flagship Project SHIFT funded by Nordic Energy Research (grant number 77892).

Acknowledgments: The authors wish to thank Pierpaolo Cazzola and Jacob Teter (International Energy Agency) for their insightful comments and precious advices regarding the MoMo model and its application within the NETP 2016 study. The work presented in this paper is a result of the research activities of the SHIFT (Sustainable Horizons for Transport) project (grant number 77892), funded by The Nordic Energy Research.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Abbreviations

4DS	4 Degree Scenario
BE	Battery Electric
BECCS	Bio-Energy with Carbon Capture Storage
CCS	Carbon Capture Storage
CNS	Carbon Neutral Scenario
CO_2	Carbon Dioxide
E4	Energy-Economy-Environmental-Engineering
ETP	Energy Technology Perspectives
EVs	Electrical Vehicles
FC	Fuel Cell
GDP	Gross Domestic Product
GHG	Greenhouse Gas

GIS	Geographical Information System
IEA	International Energy Agency
ICE	Internal Combustion Engine
JRC	Joint Research Centre
LCA	Life-Cycle Assessment
LDVs	Light Duty Vehicles
MaaS	Mobility as a Service
MoMo	Mobility Model
NER	Nordic Energy Research
NETP	Nordic Energy Technology Perspectives
TIMES	The Integrated MARKAL-EFOM System
TTW	Tank-To-Wheels
WTT	Well-To-Tank
WTW	Well-To-Wheels

Appendix A

The Appendix A provide additional insights on the methodological framework applied within the NETP 2016 study. In particular, Appendix A.1 deepens into the reasoning of the urban and non-urban dimension characterization and how is achieved quantitatively. Appendix A.2 provides additional insights on the scenarios conceptualization and on how foresight theory is applied.

Appendix A.1 Urban Dimension towards Sustainable Development

For the first time within the ETPs, ETP 2016 and NETP 2016 analyze the urban dimension with a special focus and dedicated tools. When looking at sustainable development, the urban dimension is identified as central for different reasons. Within the Nordic region, 85% (2013) of the population lives in cities, and the urbanization rate is expected to triplicate within the next 35 years [16] (p. 42). Therefore, the urban areas will increasingly play a major role in terms of energy demand, in particular with respect to transport and buildings. In addition, cities have a unique potential for deploying specific sustainable technologies, which are benefiting from high population density (economy of scale) and relatively short distances, such as district heating and EVs. Lastly, Nordic capitals are already innovation hubs and global leaders in supporting high quality public transport and non-motorized modes, besides setting more ambitious strategies than their national governments, as Copenhagen's 2025 carbon neutrality ([16], pp. 108, 117).

Concerning the transport sector characterization, geographical information system (GIS) analyses are used to identify high-density urban areas suitable of high capacity public transport (e.g. railways). Passenger two and three wheelers are assumed exclusively urban, passenger air transport is entirely allocated to non-urban areas together with heavy freight trucks, rail and sea transport ([1], p. 219). Vehicle stocks allocation is based on the United Nations database provided by [86]. Mileages characterization are based on average travel time and speed in urban areas, and fuel economies are assumed 10% worse in urban areas than the original values ([16], pp. 61, 112). Lastly, two additional models, TIMES-Helsinki-Metro and TIMES-Oslo, are used to analyze two "real city cases", the Helsinki region and the city of Oslo respectively. However, such studies are not linked to the main analytical framework [87,88]. Thus, due to their freestanding nature, such analyses are not included in this review.

Appendix A.2 Scenario Types in the NETP 2016

NETP 2016 involves a mix of scenario types from a reference year (2013) to 2050. Based on the nomenclature of Börjeson et al. [89] for foresight theory conceptualization, those scenarios represent a predictive approach (forecast and what if types) able to identify the most likely development to happen given specific conditions, and a normative approach addressing the question: "How can a specific target be reached?" [89]. The first scenario type usually provides an insight on how far the development will go compared to the desirable future if no actions would be taken or under specific choices (bifurcation point), the second aims at identifying changes needed to reach the end goal vision.

Different types of argumentations are articulated within the NETP 2016 in order to justify a specific picture of the future, in both approaches (predictive and normative). For the predictive case, such argumentations serve to justify the solidity of the selected future, convincing the audience that all the other possibilities are less likely to happen given certain conditions. For the normative case, argumentations are used to filter in or out possibilities considered incoherent or infeasible with the aimed target (desirable future), as for example, a deployment of a specific technology. These argumentations usually have their roots in the observation of the present situation (historical data).

An example of how the normative approach is applied within the NETP 2016 is represented by the case of FC electric vehicles, which, in the CNS and 4DS, do not cover a main role compared to other technologies, for different reasons. Firstly, hydrogen production is limited by the competition with other forms of electricity storage, such as pumped hydro, and by the limited availability of low cost excess electricity in the portrayed future, where the development of a better integrated market for electricity is considered pivotal across scenarios. The second argumentation is related to the investment in infrastructures (as e.g. centralized production and adequate local distribution) that is, nowadays, considered risky for the hydrogen case ([16], p. 69). Thus, FC electric vehicles are almost excluded from being a possible solution to Nordic mobility, through argumentations regarding their possible deployment in the chosen future. Such argumentations, based on present scientific knowledge, serve to assess the feasibility (or coherence) of such technology choice in relation to the future vision that practitioners wish to achieve. Since some specific features of the desired future are clearly defined (e.g., better integrated electricity market), the context where technologies will act is already in part decided, and such argumentations act in order to filter in or out specific possibilities to be taken into account in the final solution.

This process is applied in different cases to mold the backbone of the targeted vision of the future. One example is the recent case of the so called "diesel gate", which is assumed to represent a discouraging event for the diesel vehicle market that will eventually lead to a stabilization of sales in the next future within the 4DS scenario ([16], p. 66). Another example is the pioneering experience of Norway in employing winning policies supporting EVs diffusion that is brought as an encouraging motivation to believe that the Nordics can reach world record figures in terms of BE electric vehicles deployment within 2050 based on the Norwegian experience, as outlined by the CNS results ([16], p. 64). On the other hand, the already wide spread of policies limiting car ownership and car operation among the Nordics, such as fuel and vehicle taxes or road pricing, are considered a possible reason for inefficacy of further future measures encouraging transport avoidance or modal shift from cars to, for example, public transport (due to limited potential). For this reason, vehicle ownership per capita is assumed to grow, with the same slow trend as today within both the 4DS and the CNS ([16], p. 68).

References

1. International Energy Agency. *Energy Technology Perspectives 2016: Towards Sustainable Energy Systems*; IEA Publications: Paris, France, 2016.
2. International Energy Agency. *Energy Technology Perspectives 2015*; IEA Publications: Paris, France, 2015.
3. International Transport Forum. *Transport CO_2 and Paris Agreement Reviewing the Impact of Nationally Determined Contributions*; ITF Publications: Paris, France, 2018.
4. International Energy Agency. *Energy Technology Perspectives 2014*; IEA Publications: Paris, France, 2014.
5. International Energy Agency. *Nordic EV Outlook 2018*; IEA Publications: Paris, France, 2018.
6. Nordic Council of Ministers. *Energy and Transport*; TemaNord: Copenhagen, Denmark, 2014. [CrossRef]
7. Nordic Action Group on Climate and Energy. *Nordic Transport Ways*; Global Utmaning: Stockholm, Sweden, 2015.
8. Lopion, P.; Markewitz, P.; Robinius, M.; Stolten, D. A review of current challenges and trends in energy systems modeling. *Renew. Sustain. Energy Rev.* **2018**, *96*, 156–166. [CrossRef]

9. Münster, M.; Morthorst, P.E.; Larsen, H.V.; Bregnbæk, L.; Werling, J.; Lindboe, H.H.; Ravn, H. The role of district heating in the future Danish energy system. *Energy* **2012**, *48*, 47–55. [CrossRef]
10. Petrović, S.N.; Karlsson, K.B. Residential heat pumps in the future Danish energy system. *Energy* **2016**, *114*, 787–797. [CrossRef]
11. Tattini, J.; Gargiulo, M.; Karlsson, K. Reaching carbon neutral transport sector in Denmark—Evidence from the incorporation of modal shift into the TIMES energy system modeling framework. *Energy Policy* **2018**, *113*, 571–583. [CrossRef]
12. Börjesson, M.; Ahlgren, E.O.; Lundmark, R.; Athanassiadis, D. Biofuel futures in road transport—A modeling analysis for Sweden. *Transp. Res. Part D Transp. Environ.* **2014**, *32*, 239–252. [CrossRef]
13. Tattini, J.; Mulholland, E.; Venturini, G.; Ahancian, M.; Gargiulo, M.; Balyk, O. A Long-Term Strategy to Decarbonise the Danish Inland Passenger Transport Sector. In *Limiting Global Warming to Well Below 2 °C: Energy System Modelling and Policy Development*; Giannakidis, G., Karlsson, K., Labriet, M., Ó Gallachóir, B., Eds.; Lecture Notes in Energy; Springer: Berlin, Germany, 2018; Volume 64, pp. 137–153. [CrossRef]
14. Shafiei, E.; Davidsdottir, B.; Leaver, J.; Stefansson, H.; Asgeirsson, E.I. Potential impact of transition to a low-carbon transport system in Iceland. *Energy Policy* **2014**, *69*, 127–142. [CrossRef]
15. Rosenberg, E.; Fidje, A.; Espegren, K.A.; Stiller, C.; Svensson, A.M.; Møller-Holst, S. Market penetration analysis of hydrogen vehicles in Norwegian passenger transport towards 2050. *Int. J. Hydrogen Energy* **2010**, *35*, 7267–7279. [CrossRef]
16. International Energy Agency, Nordic Energy Research. *Nordic Energy Technology Perspectives 2016*; IEA Publications: Paris, France; Oslo, Norway, 2016. [CrossRef]
17. Web of Science. Available online: https://www.webofknowledge.com (accessed on 13 March 2019).
18. DTU Findit. Available online: https://findit.dtu.dk (accessed on 13 March 2019).
19. Scopus. Available online: https://www.scopus.com (accessed on 13 March 2019).
20. International Energy Agency. Nordic Energy Technology Perspectives 2016. Available online: https://www.iea.org/etp/nordic/ (accessed on 12 July 2017).
21. Liu, Z.; Wu, Q.; Nielsen, A.; Wang, Y. Day-Ahead Energy Planning with 100% Electric Vehicle Penetration in the Nordic Region by 2050. *Energies* **2014**, *7*, 1733–1749. [CrossRef]
22. Graabak, I.; Wu, Q.; Warland, L.; Liu, Z. Optimal planning of the Nordic transmission system with 100% electric vehicle penetration of passenger cars by 2050. *Energy* **2016**, *107*, 648–660. [CrossRef]
23. Juul, N.; Meibom, P. Road transport and power system scenarios for Northern Europe in 2030. *Appl. Energy* **2012**, *92*, 573–582. [CrossRef]
24. Taljegard, M.; Göransson, L.; Odenberger, M.; Johnsson, F. Impacts of electric vehicles on the electricity generation portfolio—A Scandinavian-German case study. *Appl. Energy* **2019**, *235*, 1637–1650. [CrossRef]
25. Ravn, H. Balmorel Energy System Model. Available online: http://www.balmorel.com/ (accessed on 12 July 2017).
26. Bright, R.M.; Strømman, A.H. Fuel-Mix, Fuel Efficiency, and Transport Demand Affect Prospects for Biofuels in Northern Europe. *Environ. Sci. Technol.* **2010**, *44*, 2261–2269. [CrossRef] [PubMed]
27. Krook-Riekkola, A.; Sandberg, E. Net-Zero CO_2-Emission Pathways for Sweden by Cost-Efficient Use of Forestry Residues. In *Limiting Global Warming to Well Below 2 °C: Energy System Modelling and Policy Development*; Giannakidis, G., Karlsson, K., Labriet, M., Ó Gallachóir, B., Eds.; Lecture Notes in Energy; Springer: Berlin, Germany, 2018; Volume 64, pp. 123–136.
28. Meibom, P.; Karlsson, K. Role of hydrogen in future North European power system in 2060. *Int. J. Hydrogen Energy* **2010**, *35*, 1853–1863. [CrossRef]
29. Sørensen, B. A renewable energy and hydrogen scenario for northern Europe. *Int. J. Energy Res.* **2008**, *32*, 471–500. [CrossRef]
30. Koljonen, T.; Pursiheimo, E.; Gether, K.; Jøregensen, K. *System Analysis and Assessment of Technological Alternatives for Nordic H2 Energy Foresight*; Risø National Laboratory: Roskilde, Denmark, 2004.
31. Klitkou, A.; Bolwig, S.; Coenen, L.; Solér, O.; Scordato, L. *Technology Opportunities in Nordic Energy System Transitions (TOP-NEST)*; Nordic Institute for Studies in Innovation, Research and Education: Oslo, Norway, 2015.
32. Seljom, P.; Rosenberg, E. A Scandinavian Transition Towards a Carbon-Neutral Energy System. In *Limiting Global Warming to Well Below 2 °C: Energy System Modelling and Policy Development*; Giannakidis, G., Karlsson, K., Labriet, M., Gallachóir, B., Eds.; Lecture Notes in Energy; Springer: Berlin, Germany, 2018; Volume 64, pp. 105–121.

33. Pursiheimo, E.; Holttinen, H.; Koljonen, T. Path toward 100% renewable energy future and feasibility of power-to-gas technology in Nordic countries. *IET Renew. Power Gener.* **2017**, *11*, 1695–1706. [CrossRef]
34. Loulou, R.; Goldstein, G.; Kanudia, A.; Lehtilä, A.; Remme, U. Documentation for the TIMES Model—Part I: TIMES Concepts and Theory. Available online: https://iea-etsap.org/index.php/documentation (accessed on 12 July 2017).
35. Sovacool, B.K. Contestation, contingency, and justice in the Nordic low-carbon energy transition. *Energy Policy* **2017**, *102*, 569–582. [CrossRef]
36. Haasz, T.; Vilchez, J.J.; Kunze, R.; Deane, P.; Fraboulet, D.; Fahl, U.; Mulholland, E. Perspectives on decarbonizing the transport sector in the EU-28. *Energy Strateg. Rev.* **2018**, *20*, 124–132. [CrossRef]
37. World Energy Council, IBM Corporation, Paul Scherrer Institute. *Global Transport Scenarios 2050*; World Energy Council: London, UK, 2011.
38. Fulton, L.; Cazzola, P.; Cuenot, F. IEA Mobility Model (MoMo) and its use in the ETP 2008. *Energy Policy* **2009**, *37*, 3758–3768. [CrossRef]
39. International Energy Agency. Modelling of the Transport Sector in the Mobility Model 2017. Available online: https://www.iea.org/etp/etpmodel/transport/ (accessed on 12 July 2017).
40. Cuenot, F.; Fulton, L.; Staub, J. The prospect for modal shifts in passenger transport worldwide and impacts on energy use and CO_2. *Energy Policy* **2012**, *41*, 98–106. [CrossRef]
41. Yeh, S.; Mishra, G.S.; Fulton, L.; Kyle, P.; McCollum, D.L.; Miller, J.; Cazzola, P.; Teter, J. Detailed assessment of global transport-energy models' structures and projections. *Transp. Res. Part D Transp. Environ.* **2016**, 1–16. [CrossRef]
42. Schipper, L.; Marie-Lilliu, C.; Gorham, R. *Flexing the Link between Transport and Greenhouse Gas Emissions*; IEA Publications: Paris, France, 2000.
43. Cazzola, P.; (International Energy Agency, Paris, France). Personal communication, 2017.
44. Wråke, M.; (Swedish Energy Research Centre—Energiforsk, Stockholm, Sweden). Personal communication, 2017.
45. Daly, H.E.; Ramea, K.; Chiodi, A.; Yeh, S.; Gargiulo, M.; Gallachóir, B.Ó. Incorporating travel behaviour and travel time into TIMES energy system models. *Appl. Energy* **2014**, *135*, 429–439. [CrossRef]
46. Pye, S.; Daly, H. Modelling sustainable urban travel in a whole systems energy model. *Appl. Energy* **2015**, *159*, 97–107. [CrossRef]
47. Tattini, J.; Ramea, K.; Gargiulo, M.; Yang, C.; Mulholland, E.; Yeh, S.; Karlsson, K. Improving the representation of modal choice into bottom-up optimization energy system models—The MoCho-TIMES model. *Appl. Energy* **2018**, *212*, 265–282. [CrossRef]
48. Cayla, J.-M.; Maïzi, N. Integrating household behavior and heterogeneity into the TIMES-Households model. *Appl. Energy* **2015**, *139*, 56–67. [CrossRef]
49. Salvucci, R.; Tattini, J.; Gargiulo, M.; Lehtilä, A.; Karlsson, K. Modelling transport modal shift in TIMES models through elasticities of substitution. *Appl. Energy* **2018**, *232*, 740–751. [CrossRef]
50. Connolly, D. Economic viability of electric roads compared to oil and batteries for all forms of road transport. *Energy Strateg. Rev.* **2017**, *18*, 235–249. [CrossRef]
51. Ahjum, F.; Merven, B.; Stone, A.; Caetano, T. Road transport vehicles in South Africa towards 2050: Factors influencing technology choice and implications for fuel supply. *J. Energy S. Afr.* **2018**, *29*, 33–55. [CrossRef]
52. Ishimoto, Y.; Kurosawa, A.; Sasakura, M.; Sakata, K. Significance of CO_2 -free hydrogen globally and for Japan using a long-term global energy system analysis. *Int. J. Hydrogen Energy* **2017**, *42*, 13357–13367. [CrossRef]
53. Oshiro, K.; Masui, T. Diffusion of low emission vehicles and their impact on CO2 emission reduction in Japan. *Energy Policy* **2015**, *81*, 215–225. [CrossRef]
54. Kawakami, Y.; Komiyama, R.; Fujii, Y. Penetration of Electric Vehicles toward 2050: Analysis Utilizing an Energy System Model Incorporating High-Temporal-Resolution Power Generation Sector. *IFAC-PapersOnLine* **2018**, *51*, 598–603. [CrossRef]
55. Teir, S.; Tsupari, E.; Arasto, A.; Koljonen, T.; Kärki, J.; Lehtilä, A.; Kujanpää, L.; Aatos, S.; Nieminen, M. Prospects for application of CCS in Finland. *Energy Procedia* **2011**, *4*, 6174–6181. [CrossRef]
56. Victor, N.; Nichols, C.; Zelek, C. The U.S. power sector decarbonization: Investigating technology options with MARKAL nine-region model. *Energy Econ.* **2018**, *73*, 410–425. [CrossRef]
57. Huang, W.; Chen, W.; Anandarajah, G. The role of technology diffusion in a decarbonizing world to limit global warming to well below 2 °C: An assessment with application of Global TIMES model. *Appl. Energy* **2017**, *208*, 291–301. [CrossRef]

58. Simoes, S.; Nijs, W.; Ruiz, P.; Sgobbi, A.; Thiel, C. Comparing policy routes for low-carbon power technology deployment in EU—An energy system analysis. *Energy Policy* **2017**, *101*, 353–365. [CrossRef]
59. Blanco, H.; Nijs, W.; Ruf, J.; Faaij, A. Potential for hydrogen and Power-to-Liquid in a low-carbon EU energy system using cost optimization. *Appl. Energy* **2018**, *232*, 617–639. [CrossRef]
60. Schäfer, A. *Introducing Behavioral Change in Transportation into Energy/Economy/Environment Models*; World Bank policy research working paper no. WPS 6234; World Bank: Washington, DC, USA, 2012.
61. Venturini, G.; Tattini, J.; Mulholland, E.; Ó Gallachóir, B. Improvements in the representation of behaviour in integrated energy and transport models. *Int. J. Sustain. Transp.* **2018**, *13*, 294–313. [CrossRef]
62. Baptista, P.; Melo, S.; Rolim, C. Energy, Environmental and Mobility Impacts of Car-sharing Systems. Empirical Results from Lisbon, Portugal. *Procedia Soc Behav. Sci.* **2014**, *111*, 28–37. [CrossRef]
63. International Energy Agency. *Transport Energy and CO_2*; IEA Publications: Paris, France, 2009.
64. European Commission. *White Paper. Roadmap to a Single European Transport Area—Towards a Competitive and Resource Efficient Transport System*; European Commission: Brussels, Belgium, 2011.
65. Iacobucci, R.; McLellan, B.; Tezuka, T. The Synergies of Shared Autonomous Electric Vehicles with Renewable Energy in a Virtual Power Plant and Microgrid. *Energies* **2018**, *11*, 2016. [CrossRef]
66. International Energy Agency. *The Future of Trucks—Implications for Energy and the Environment*; IEA Publications: Paris, France, 2017.
67. Martinsen, K.; Torvanger, A. *Control Mechanisms for Nordic Ship Emissions*; TemaNord, Nordic Council of Ministers: Copenhagen, Denmark, 2013.
68. Gagatsi, E.; Estrup, T.; Halatsis, A. Exploring the Potentials of Electrical Waterborne Transport in Europe: The E-ferry Concept. *Transp. Res. Procedia* **2016**, *14*, 1571–1580. [CrossRef]
69. Rootzén, J.; Johnsson, F. CO_2 emissions abatement in the Nordic carbon-intensive industry—An end-game in sight? *Energy* **2015**, *80*, 715–730. [CrossRef]
70. Rydén, M.; Lyngfelt, A.; Langørgen, Ø.; Larring, Y.; Brink, A.; Teir, S.; Havåg, H.; Karmhagen, P. Negative CO_2 Emissions with Chemical-Looping Combustion of Biomass—A Nordic Energy Research Flagship Project. *Energy Procedia* **2017**, *114*, 6074–6082. [CrossRef]
71. Anthonsen, K.L.; Aagaard, P.; Bergmo, P.E.; Erlström, M.; Fareide, J.I.; Gislason, S.R.; Mortensen, G.M.; Snæbjörnsdottir, S.Ó. CO_2 Storage Potential in the Nordic Region. *Energy Procedia* **2013**, *37*, 5080–5092. [CrossRef]
72. Mustapha, W.F.; Bolkesjø, T.F.; Martinsen, T.; Trømborg, E. Techno-economic comparison of promising biofuel conversion pathways in a Nordic context—Effects of feedstock costs and technology learning. *Energy Convers. Manag.* **2017**, *149*, 368–380. [CrossRef]
73. Börjesson, M.; Grahn, M.; Ahlgren, E. *Transport Biofuel Futures in Energy-Economic Modeling—A Review*; The Swedish Knowledge Centre for Renewable Transportation Fuels: Göteborg, Sweden, 2013.
74. Brynolf, S.; Taljegard, M.; Grahn, M.; Hansson, J. Electrofuels for the transport sector: A review of production costs. *Renew. Sustain. Energy Rev.* **2018**, *81*, 1887–1905. [CrossRef]
75. Goldmann, A.; Sauter, W.; Oettinger, M.; Kluge, T.; Schröder, U.; Seume, J.; Friedrichs, J.; Dinkelacker, F. A Study on Electrofuels in Aviation. *Energies* **2018**, *11*, 392. [CrossRef]
76. Mustapha, W.F.; Kirkerud, J.G.; Bolkesjø, T.F.; Trømborg, E. Large-scale forest-based biofuels production: Impacts on the Nordic energy sector. *Energy Convers. Manag.* **2019**, *187*, 93–102. [CrossRef]
77. Sgobbi, A.; Nijs, W.; De Miglio, R.; Chiodi, A.; Gargiulo, M.; Thiel, C. How far away is hydrogen? Its role in the medium and long-term decarbonisation of the European energy system. *Int. J. Hydrogen Energy* **2016**, *41*, 19–35. [CrossRef]
78. Næss, P.; Jensen, O.B. Urban structure matters, even in a small town. *J. Environ. Plan Manag.* **2004**, *47*, 35–57. [CrossRef]
79. Krumdieck, S.; Page, S.; Dantas, A. Urban form and long-term fuel supply decline: A method to investigate the peak oil risks to essential activities. *Transp. Res. Part A Policy Pract.* **2010**, *44*, 306–322. [CrossRef]
80. Forsberg, J.; Krook-Riekkola, A. Supporting Cities' Emission Mitigation StrategieS: Modelling Urban Transport in a Times Energy System Modelling Framework. In Proceedings of the 17th International Conference on Urban Transport and the Environment, University of Rome 'La Sapienza', Rome, Italy, 5–7 September 2017; Ricci, S., Brebbia, C.A., Eds.; Wessex Institute: Ashurst, UK, 2017; pp. 15–25. [CrossRef]
81. Lind, A.; Espegren, K. The use of energy system models for analysing the transition to low-carbon cities—The case of Oslo. *Energy Strateg. Rev.* **2017**, *15*, 44–56. [CrossRef]

82. Sovacool, B.K.; Noel, L.; Kester, J.; Zarazua de Rubens, G. Reviewing Nordic transport challenges and climate policy priorities: Expert perceptions of decarbonisation in Denmark, Finland, Iceland, Norway, Sweden. *Energy* **2018**, *165*, 532–542. [CrossRef]
83. Joint Research Centre. *Well-To-Wheels Report Version 4.a—Well-To-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context*; Publications Office of the European Union: Luxembourg, 2014. [CrossRef]
84. Joint Research Centre. *Well-To-Tank Report Version 4.0—Well-To-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context*; Publications Office of the European Union: Luxembourg, 2013. [CrossRef]
85. Stocker, T.F.; Qin, D.; Plattner, G.-K.; Tignor, M.; Allen, A.K.; Boschung, J.; Nauels, A.; Xia, Y.; Bex, V.; Midgley, P.M. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2013.
86. United Nations, Department of Economic and Social Affairs. *World Urbanization Prospects: The 2014 Revision, CD-ROM Edition 2014*; United Nations Publications: New York, NY, USA, 2015.
87. Koljonen, T.; (Technical Research Centre of Finland—VTT, Espoo, Finland). Personal communication, 2017.
88. Espegren, K.A.; (Institute for Energy Technology, Kjeller, Norway). Personal communication, 2017.
89. Börjeson, L.; Höjer, M.; Dreborg, K.H.; Ekvall, T.; Finnveden, G. Scenario types and techniques: Towards a user's guide. *Futures* **2006**, *38*, 723–739. [CrossRef]

Paper III

Modelling transport modal shift in TIMES models through elasticities of substitution

Applied Energy 232 (2018) 740–751

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Modelling transport modal shift in TIMES models through elasticities of substitution

Raffaele Salvucci[a,*], Jacopo Tattini[a], Maurizio Gargiulo[b], Antti Lehtilä[c], Kenneth Karlsson[a]

[a] *Technical University of Denmark, Department of Management Engineering, Produktionstorvet, Building 426, 2800 Kgs. Lyngby, Denmark*
[b] *E4SMA, Via Livorno 60, 10144 Turin, Italy*
[c] *VTT Technical Research Centre of Finland, P.O. Box 1000, 02044 VTT, Finland*

HIGHLIGHTS

- Novel methodology to endogenise modal shift in energy system models.
- Substitution elasticities are adopted to regulate transport modal shares.
- Modal demands self-adjust elastically in response to shadow price changes.
- Sensitivity analysis on elasticities reveals substitution saturation.
- Interactions between novel methodology and traditional model structure explained.

ARTICLE INFO

Keywords:
Elasticities
Energy system modeling
Modal shift
TIMES models
Transport

ABSTRACT

Several efforts have been directed lately towards the endogenisation of transport modes competition in Energy/Economy/Environment/Engineering (E4) models. TIMES-DKEMS is a novel methodology paving the way for applying elasticities of substitution to incorporate transport modal shift into TIMES (The Integrated MARKAL-EFOM System) models. Substitution elasticities are defined for four transport demand aggregates, each corresponding to a different distance range class. Within an aggregate, modal demands can adjust their levels according to the defined substitution elasticity and in response to changes of their shadow prices relative to a reference case. The total volume of the transport demand over the aggregate is conserved and modal shift potentials are implemented to guarantee realistic dynamics. The behavior of TIMES-DKEMS is tested under an arbitrary environmental policy, an increasingly stringent bound on CO_2 emissions. Modal shares are compared with the standard version of TIMES-DK. Results show that in 2050, 11% of car mobility demand is substituted by more efficient and less costly modes such as train and coach. A sensitivity analysis on the values of substitution elasticities indicates that higher absolute values correspond to larger modal shift. Finally, other model constraints, such as mode-specific travel patterns, interact with the substitution mechanism resulting in a modal shift containment.

1. Introduction

Transport is a key driver and key enabler of economic growth and plays a fundamental role in supporting quality of life. However, it is also responsible for approximately 28% of total final energy use and for 23% of the world energy-related CO_2 emissions [1]. It is the sector that experienced the highest growth in emissions since 1990, and presents the least diversified portfolio of energy supply sources, relying mainly on petroleum products [2]. Transport is widely considered the most complicated energy sector to decarbonise, due to multiple reasons. Transportation activity is strongly coupled with gross domestic product (GDP), incomes and population levels, which are increasing factors for most countries [3]. Mobility demand per capita in countries outside the Organisation for Economic Co-operation and Development (OECD) is still below the levels of OECD countries, but is expected to grow at a faster pace. Some low-carbon transport technologies have appeared in the market [4], but their high upfront costs still hamper a wide adoption, thus making policy support still a requirement to enhance their acceptability [5,6]. Moreover, the uptake of new transportation technologies is slowed down by the slow turnover rate of the existing

---

* Corresponding author.
E-mail address: rafs@dtu.dk (R. Salvucci).

https://doi.org/10.1016/j.apenergy.2018.09.083
Received 5 July 2018; Received in revised form 31 August 2018; Accepted 8 September 2018
Available online 14 September 2018

Nomenclature

Variables

DM_k	demand aggregate [Mpkm]
$DM_{k,i}$	modal demand segment [Mpkm]
$sm_{k,j,i}$	modal demand segment step variable in the low direction [Mpkm]
$sn_{k,j,i}$	modal demand segment step variable in the up direction [Mpkm]
$zm_{j,k}$	aggregate demand step variable in the low direction [Mpkm]
$zn_{j,k}$	aggregate demand step variable in the up direction [Mpkm]
$p_{k,i}$	modal demand segment shadow price [M Danish Kr./Mpkm]

Parameters

$DM^0_{k,i}$	modal demand segment in the reference case [Mpkm]
σ_k	elasticity of substitution [–]
$\Delta^{lo}_{k,i}$	modal shift potential in the low direction [%]
$\Delta^{up}_{k,i}$	modal shift potential in the up direction [%]
$\beta_{k,i}$	step variable width [Mpkm]
$p^-_{k,ji}$	demand decrease price function coefficients [M Danish Kr./Mpkm]
$p^+_{k,ji}$	demand increase price function coefficients [M Danish Kr./Mpkm]
$\delta_{i,k}$	user-defined substitution rate [–]
m	number of linearization step in the low direction [–]
n	number of linearization step in the up direction [–]
N_k	number of component demands composing the aggregate [–]

Indices

k	aggregate index ($k = XS, S, M, L$)
j	linearization step index ($j = 1,\ldots, m; n$)
i	component demand index ($i = 1,\ldots, N_k$)
t	year index ($t = 2010,\ldots, 2050$)

Superscripts

o	reference case
‘	after substitution

Glossary

BU	bottom-up
BY	base year
CES	constant elasticity of substitution
CO_2	carbon dioxide
DKE	Denmark east
DKW	Denmark west
E4	energy-economy-environment-engineering
ETSAP	Energy Technology Systems Analysis Program
GDP	gross domestic product
GHG	greenhouse gas
H	hybrid
ICE	internal combustion engine
IEA	International Energy Agency
L	long distance
LTM	Landstrafikmodellen, Danish National Transport Model
M	medium distance
MNL	multinomial logit
O&M	operation and maintenance
OECD	Organisation for Economic Co-operation and Development
Pkm	Passenger-kilometre
S	short distance
TD	top-down
TIMES	The Integrated Markal Efom System
TIMES-DK	TIMES model of Denmark
TIMES-DKEMS	TIMES model of Denmark with Elastic Modal Shift
TIMES-DKMS	TIMES model of Denmark with Modal Shift
Tkm	Tonne-kilometre
TU	The Danish National Travel Survey
XS	extra short distance

vehicle fleet and the lock-in effect originated by the existing infrastructure. So far, efforts to reduce transport emissions through technological improvements and fuel standards have been offset by the increase of activity. The International Energy Agency (IEA) estimates in its baseline scenario an increase of nearly 75% in global transport energy consumption by 2050 and almost a doubling of associated CO_2 emissions worldwide [7]. IEA suggests a combination of three technological and behavioral measures to be promoted concurrently: avoiding travel, shifting to different modes and improving vehicle efficiency [2,7]. Another set of measures recommended includes development of efficient technologies, changes in pricing and budgeting, attitudinal change, infrastructure supply, innovative institutional arrangements and development of new methods [8]. Therefore, it is widely recognized that the behavioral dimension is central to leading the transition to a low-carbon transportation sector.

Energy system models are powerful tools for supporting long-term decision making in the energy sector. In this study we focus on a specific family of them, the TIMES models, belonging to the category of energy-economy-environmental-engineering (E4) optimization models. TIMES models have been used for more than three decades to identify least-cost resources and technology deployment pathways towards greenhouse gas (GHG) emission-free energy systems, exploring alternative scenarios under several constraints and for different countries such as Ireland [9], California [10,11], Canada [12], China [13] or even globally [14]. E4 models stand for their detailed representation of the technological, economic and environmental dimensions of the integrated energy system and their capability to explore decarbonisation pathways, considering cross-sectoral dynamics and synergies. Nonetheless, E4 models are still weak at depicting human behavior driving consumer's choice [15,16]. Since individuals' preferences are a fundamental aspect of decision-making in the transportation sector, the behavioral dimension should be embedded in E4 models to depict real households' behavior and their preferences towards modal choice and use of transportation technologies [17]. This study moves a step forward in the representation of behavior in transport in energy system models proposing TIMES-DKEMS, a novel methodology that integrates endogenous modal shift within bottom-up (BU) optimization E4 models through the use of elasticities of substitution. Incorporating endogenous modal shift enables the direct assessment of its potential contribution to a low carbon future energy system, allowing dedicated policy analysis. This study reviews the modeling of modal choice in transport and energy system models in Section 2. Section 3 describes the approach of TIMES-DKEMS in all its aspects. The results for a Baseline scenario and for the sensitivity scenarios are analyzed in Section 4, which also provides some insights on the new capabilities of the model. Section 5 discusses the main advantages and shortcomings of the methodology proposed compared to other models in the literature and recommends the direction for future research, aimed at improving the representation of behavior in transport in E4 models. Finally, Section 6 presents the conclusion.

2. Literature review

Modal shift consists of a transfer of mobility demand across modes of transport, as a result of changes in modal choice. Modal choice, in turn, consists of the choice of a mode of transport from two or more alternatives. Considering that modal choice is always among a finite set of mutually exclusive alternatives, this is a typical case of discrete choice problem, which can be represented by discrete choice models, as well described by [18–20]. Transport models have been simulating modal choice for a long time to analyze short and mid-term developments of the transport system of a country, region or city as, for example, in the case of Ireland [21], California [22] and Thailand [23]. Thanks to their highly disaggregated description of the population and their ability to base decisions on many attributes, transport models are valid tools for assessing households' modal choice. On the other hand, in the field of energy system models, the representation of modal choice is an innovative topic. Thanks to the inclusion of simulation methods in the model structure, top-down (TD) [24] and hybrid (H) [25,26] E4 models are able to simulate modal choice through constant elasticities of substitution (CES) and multinomial logit (MNL) functions, which have been used for this purpose for more than four decades, thus being very reliable. Instead, BU optimization energy system models lag behind TD and H models regarding their ability to represent modal shift. Traditional approaches to represent modal choice, e.g. CES and MNL functions, do not fit directly in the optimization framework, (normally based on linear programming). Thus for this class of models, the research on new modeling techniques for representing modal choice is a cutting-edge topic. A review of the representation of behavior in integrated energy and transport models recognized two main approaches to incorporate behaviorally-realistic modal choice into BU E4 models [15]. The first approach consists of linking the E4 model with an external transport simulation model that incorporates the behavioral features and that determines the modal shares, e.g. through CES [27], MNL functions [28,29], or through elasticities [30]. The second approach consists of determining modal shares directly within the E4 model, by broadening its classical framework to integrate some transport-specific variables relevant to modal choice, such as travel time budget and transport infrastructures [31–33] or modal level of service and consumers' modal perception [34,35]. The methodology developed and presented in this study to integrate modal shift within BU optimization E4 models falls in the second category of such taxonomy. The methodology proposed uses substitution elasticities to mimic modal shift, as described in detail in Section 3. Elasticities are already used to simulate modal shift in TD energy models as in [36,37,24], in H energy models as in [38,25] or in dedicated transport scenario analysis [39]. However, to the authors' knowledge, their application for modal shift modelling in BU optimization models has not been investigated by any existing study in the literature. The present study aims at closing such a gap with TIMES-DKEMS.

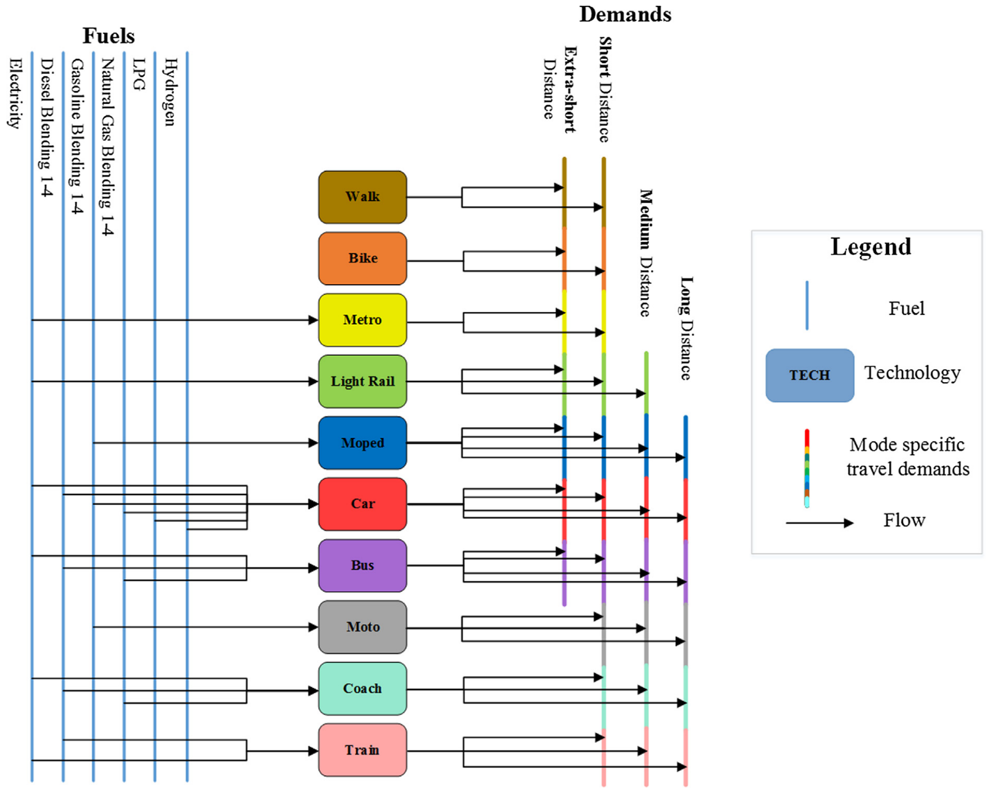


Fig. 1. Standard inland passenger transport sector structure in TIMES-DK. For simplicity, each of the colored segments, representing a portion of each distance range class covered by a specific mode, is represented by the same length. However, the magnitudes of the specific modal demands are usually different. Modified from [31].

3. Methodology

The approach presented in this study allows to incorporate passenger transport modal shift into TIMES models, by using elastic demand functions. While traditionally TIMES models included only the linearized own-price elasticities, recently the elastic demand functions formulation has been generalized, in order to represent elastic substitution among demands by [40]. The approach proposed in this study applies such formulation to simulate transport modal shift. The methodology is developed within the standalone transportation sector of TIMES-DK, the TIMES model representing the complete Danish energy system [41]. This version is called TIMES-DKEMS (TIMES-DK with elastic modal shift).

The full description of the proposed methodology is addressed in the following sub-sections. Section 3.1 introduces the TIMES modelling framework, TIMES-DK and TIMES-DKEMS. Section 3.2 describes the structure of the inland passenger transport sector in TIMES-DK and in TIMES-DKEMS. Section 3.3 describes the use of elasticity of substitution to simulate modal shift endogenously, while Section 3.4 addresses how additional constraints contribute to regulate modal shift. Finally, Section 3.5 defines the scenario used to test TIMES-DKEMS.

3.1. TIMES-DK and TIMES-DKEMS

TIMES (The Integrated MARKAL-EFOM System) model generator is developed and maintained by the Energy Technology Systems Analysis Programme (ETSAP), a Technology Collaboration Programme of the IEA. TIMES models are BU technology-rich energy system models suited for medium/long-term analysis and planning of a national, regional or even city-level energy system. Moreover, TIMES is a techno-economic, partial equilibrium model generator assuming full foresight and perfectly competitive markets. TIMES models are linear optimization problems whose solution is determined as the minimization of the sum of the total system costs discounted to a reference year, subject to user-defined technological, environmental, resource availability and policy restrictions. The type of inputs used to build TIMES models are typically exogenous service demand curves, supply curves and techno-economic parameters for each technology represented in the model. TIMES outputs are investments, operation and import/export levels, optimal for the energy system as a whole, marginal prices of the energy commodities, emission levels and costs. A detailed description of TIMES is provided by [42].

TIMES-DK is a multi-regional model geographically aggregated into two regions: Denmark East (DKE) and Denmark West (DKW). It is divided into five sectors, viz., supply, power and heat, industry, residential and transport. TIMES-DK is calibrated for the base year (BY) 2010 and has technological and economic projections up to 2050. This time horizon is sub-divided into shorter periods of various duration, most commonly 1–5 years [41]. In turn, every year comprises 32 non-sequential time slices, representing seasonal (4 seasons), weekly (working/non-working days) and daily variations.

TIMES-DKEMS is a lean version of TIMES-DK that represents the Danish transport sector on a standalone basis. A basic supply sector is also included, which describes the international fuel market, but omits most of the production fuel chains (such as hydrogen and electricity). Thus, CO_2 emissions due to electricity generation are not accounted for. TIMES-DKEMS integrates endogenous modal shift only within the inland passenger sector and through elasticities of substitution. The next section describes the differences between the inland passenger transport sector structure in TIMES-DK and TIMES-DKEMS.

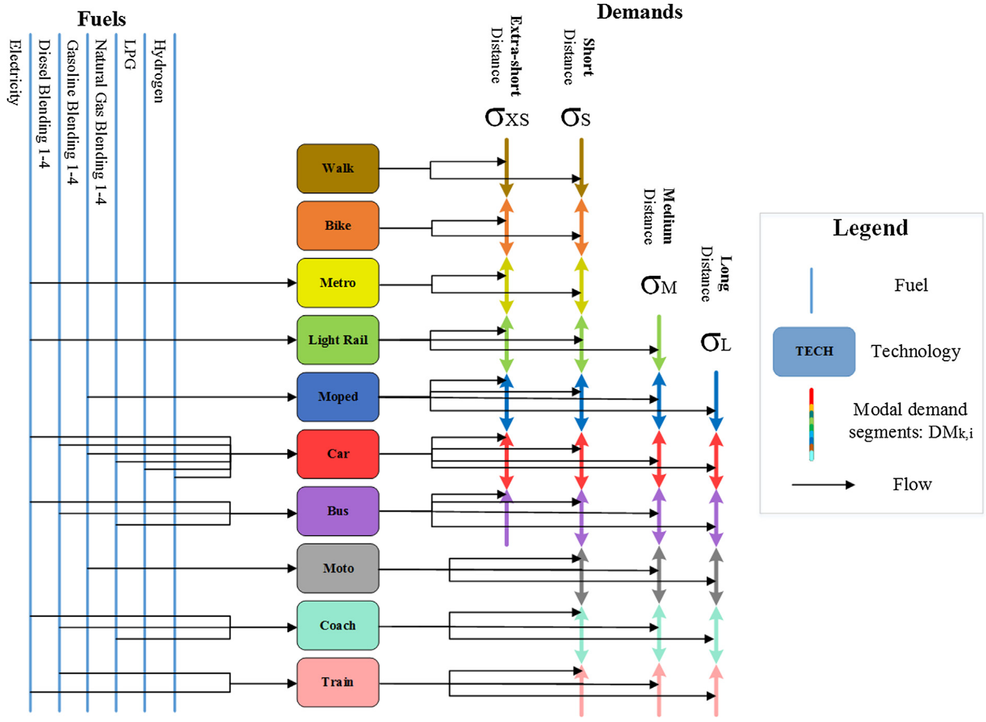


Fig. 2. Inland passenger transport sector structure in TIMES-DKEMS. For simplicity, each of the colored segments, representing a portion of each distance range class covered by a specific mode, is represented by the same length. However, the magnitudes of the specific modal demands are usually different.

3.2. Overview of the inland passenger transport sector in TIMES-DK and TIMES-DKEMS

In TIMES-DK, the transport sector comprehensively describes the Danish mobility service demands, the end-use transport technologies and the technologies producing the transport fuels. The transport sector includes passenger and freight transport, further split into aviation, maritime and inland sub-sectors. The inland passenger sector, which is the focus of this study, includes ten modes: car, bus, coach, rail (metro, train, light rail), 2-wheelers (motorcycle and moped) and non-motorized modes (bike and walk). The mobility service demands are defined exogenously for each mode, from the base year until the end of the modelling horizon. They are expressed as service demands: passenger-kilometer (pkm) and tonne-kilometre (tkm). Moreover, the demands for inland passenger modes are split into four classes of increasing distance range, namely extra short (*XS*, < 5 km), short (*S*, 5–25 km), medium (*M*, 25–50 km) and long (*L*, > 50 km) (Fig. 1).

The technology database for the transportation sector of TIMES-DK includes existing technologies and technologies that are available for future investments, which compete to meet the projected mobility demands. It is worth noticing that technologies can compete within a mode, but not between modes (i.e. modal shift is not possible, since every transport service demands are exogenously defined for each mode). In addition, competition between transport technologies is exclusively based on costs: TIMES seeks to meet the modal mobility demands with the portfolio of technologies characterized by the lowest levelized costs, while complying with the implemented constraints. Moreover, each mode is constrained to satisfy a specific travel pattern when meeting travel demands. Technologies in a given mode supply demand segments (*XS*, *S*, *M* and *L*) accordingly to an exogenously defined share, called travel pattern, which reflects population modal travel habits. The travel patterns adopted for the BY are the same as those already described in [31]. Additional flexibility is provided to the model to fulfil the future transport demands, by relaxing travel patterns from 2012 onwards by 2% compared to the BY.

The structure of TIMES-DKEMS allowing elastic inland passenger modal shift is presented in Fig. 2. The main difference between TIMES-DK and TIMES-DKEMS lies in the demand side structure. In TIMES-DKEMS, each distance range class k (where $k = XS, S, M, L$) represents an aggregate, where all corresponding travel demand segments $DM_{k,i}(t)$ (with $i = 1,\dots, N_k$) are grouped together and where a common elasticity of substitution σ_k is defined. In this study, the substitution elasticity defined for each aggregate is the same for all the component demands i. Moreover, substitution elasticity could be defined differently among aggregates (see Section 3.3) and for each year t of the time horizon T.

Modal demand segments composing an aggregate k ($DM_{k,i}(t)$) can endogenously adjust their levels in reaction to changes of their shadow prices compared to a reference case. However, each aggregate k is constrained to conserve its total demand after substitution. This latter condition characterizes the so-called volume-preserving variant of substitution elasticities, which is defined in [40]. Modal shift is allowed only from 2020 onwards and only for the inland passenger transport sector.

3.3. Elasticities of substitution

Energy system modelers can adopt elasticities to investigate demand variations in response to price changes driven by alternative scenario assumptions (e.g. fuel prices, availability of resources), or in response to specific set of policy measures (e.g. emission taxes, emission cap, etc.). The adoption of elastic demand functions in TIMES models requires the definition of a reference case, where the model calculates the reference shadow prices for the relevant demand commodities. In a second moment, the policies under assessment are introduced into the model, which alter the shadow prices of the demand commodities. The model determines a new solution, where the elastic demands re-arrange their levels because of changes in their shadow prices. The magnitude of the change is regulated by the elasticity value.

Since TIMES models are based on linear programming, the formulation of elasticities of substitution needs to be linearized. Such linearization was developed by [40]. For a specific aggregate k, each of the component demands i can be written as its exogenous value $DM^0_{k,i}(t)$ (identified in the reference case) plus two terms (Eq. (1)). Each of these terms represents a set of step variables used to rearrange the demand level in response to elastic price changes [40].

$$DM_{k,i}(t) = DM^0_{k,i}(t) - \sum_{j=1}^{m} sm_{k,j,i}(t) + \sum_{j=1}^{n} sn_{k,j,i}(t) \tag{1}$$

In each year t, each step variable $sm_{k,j,i}(t)$ and $sn_{k,j,i}(t)$ are bounded between zero and a width $\beta_{k,i}(t)$, where n and m (indexed by j) are the steps used to linearize the elastic response in the up and low direction respectively. Moreover, demand variation is limited, upwards and downwards, by a maximum percentage change $\Delta^{up}_{k,i}(t)$ and $\Delta^{lo}_{k,i}(t)$ declared relative to $DM^0_{k,i}(t)$. Therefore, defining n, m and $\Delta^{up,lo}_{k,i}(t)$ identifies the width $\beta_{k,i}(t)$ of each step, assuming that the aggregate demand remains at the reference value.

The demand price functions of the step variables are included in the objective function, and their coefficients are expressed by $p^{\pm}_{k,ji}(t)$ (Eq. (2)). For every demand i, each increase and decrease step has a price associated, which depends on the step itself (j), the elasticity of substitution declared for the aggregate σ_k, the exogenous demand component $DM^0_{k,i}(t)$ and the shadow price obtained from the reference case $p^0_{k,i}(t)$.

$$p^{\pm}_{k,ji}(t) = p^0_{k,i}(t)\left(\frac{DM^0_{k,i}(t) \pm (j-\frac{1}{2})\cdot\beta_{k,i}(t)}{DM^0_{k,i}(t)}\right)^{\frac{1}{\sigma_k}} \tag{2}$$

Moreover, an ulterior condition is required for having the aggregate volume preserved after substitution; such condition can be expressed as follows (Eq. (3)):

$$\begin{aligned} DM'_k(t) &= \textstyle\sum_{i=1}^{N_k} \delta_{i,k}(t)\cdot DM_{k,i}(t) = \sum_{i=1}^{N_k} \delta_{i,k}(t)\cdot DM^0_{k,i}(t) - \sum_{j=1}^{m_k} zm_{j,k}(t)\\ &\quad + \textstyle\sum_{j=1}^{n_k} zn_{j,k}(t)\\ &= DM^0_k(t) - \textstyle\sum_{j=1}^{m_k} zm_{j,k}(t) + \sum_{j=1}^{n_k} zn_{j,k}(t);\ \ \forall\ t \in T \end{aligned} \tag{3}$$

where $DM^0_k(t)$ and $DM'_k(t)$ are the weighted sums of the N_k component demands composing the aggregate k before and after substitution respectively and $\delta_{i,k}(t)$ are user-defined substitution rates between component i and aggregate k (which in the simplest case may all be assumed equal to 1). The terms $zm_{j,k}(t)$ and $zn_{j,k}(t)$ are the step variables used to linearize the elastic response of the aggregate demand relative to its own-price variation.

In this study, the own-price elasticities for all aggregates k are assumed null, and substitution rates between component demands $\delta_{i,k}(t)$ are all assumed unitary. In particular, the latter assumption is necessary to guarantee that the demand substitution retains the physical volume, e.g. forcing 1 pkm of rail transport to be substituted for each pkm of car transport [40]. In this specific case, Eq. (3) reduces to Eq. (4):

$$DM'_k(t) = \sum_{i=1}^{N_k} DM_{k,i}(t) = \sum_{i=1}^{N_k} DM^0_{k,i}(t) = DM^0_k(t)\ ;\forall\ t \in T \tag{4}$$

The model determines the new levels of component demands $DM_{k,i}(t)$ by means of maximizing the total surplus of consumers and producers represented in the system, while fulfilling all the constraints defined in the model.

3.4. Shift potentials

The shift potential is a constraint that limits the maximum and minimum demand that each mode can satisfy for each year of the time horizon and for each distance range class *k*. In TIMES-DKEMS, for a specific year *t*, each demand segment $DM_{k,i}(t)$ composing an aggregate *k* can re-adjust its level compared to its original exogenous value $DM^0_{k,i}(t)$ in both directions up or low, by a maximum percentage $\Delta^{up,lo}_{k,i}(t)$ (Eq. (5)):

$$DM^0_{k,i}(t) - \Delta^{lo}_{k,i}(t)\cdot DM^0_{k,i}(t) \leqslant DM_{k,i}(t) \leqslant DM^0_{k,i}(t) + \Delta^{up}_{k,i}(t)\cdot DM^0_{k,i}(t) \qquad (5)$$

Given the mathematical structure of the elastic demand formulation adopted for TIMES-DKEMS [40], the maximum technical variation for a specific $DM_{k,i}(t)$ is obtained when a 100% potential is assumed.

The shift potentials adopted for each demand segment $DM_{k,i}(t)$ are based on [31], where estimations are provided on the basis of the modal trip distance profiles extracted by the Danish National Travel survey (TU survey) [43]. In 2050, the different demand segments (*XS, S, M* and *L*) supplied by a specific mode are limited above by the sum of the transport demands that can shift out from all the other modes within the same distance range classes. Since the maximum shift potentials identified in [31] for 2050 exceeds the technical bound allowed by the elastic demand formulation for each demand segment, the maximum demand segment increase $\Delta^{up}_{k,i}(t)$ for each mode and each distance range class in 2050 is set up to 100% as outlined in Table 1. The only exception is represented by car, whose upward demand variations are set to zero for each *k* and for the entire time horizon. Such choice is adopted in order to be in line with other studies which address the same topic, and whose research question is the estimation of modal shift away from cars towards other modes [31,33].

The shift potentials in the low direction $\Delta^{lo}_{k,i}(t)$ are calculated similarly to the upward case, and are also based on [31]. In 2050, they are estimated assuming a complete shift from a specific mode towards all the others compatible with its distance range class and assuming a full shift. In most of the cases, the estimations found by [31] show a potential complete shift of each demand segment. For this reason, the maximum demand segment decrease assumed for each $DM_{k,i}(t)$ in 2050 is set up to - 100% (Table 1). The only exceptions are the long distance coach demand and the long distance train demand, whose maximum decrease variation estimation is 87% and 86% respectively. Lastly, in 2020, the upper and lower bound for each demand segment variation is obtained assuming a null potential in 2010 and interpolating linearly the potential defined in 2050 within the whole time horizon.

The maximum modal shifts achievable in each distance range class *k* are presented in Table 2. Since the aggregate demand is constrained to remain constant before and after substitution, the net total demand change is null. For this reason, the maximum modal shift achievable is calculated as how much of the highest contribution to the shift among the modes in the aggregate ($\Delta^{up,lo}_{k,i}(t)\cdot DM^0_{k,i}(t)$) can be accommodated among the rest of the component demands, given their shift potentials and according to the variation direction. In TIMES-DKEMS, the highest contributor to the shift potential in every distance range class is car, which can only decrease. Values shown in Table 2 represent how much of this demand can be accommodated in the rest of the demand segments.

3.5. *Scenario description*

The use of elasticities of substitution to simulate modal shift in TIMES models is hereby tested by comparing the results obtained with the standalone transportation sector of TIMES-DK (from now on simply called TIMES-DK) and TIMES-DKEMS (described in the previous sections). The two models are identical in terms of dataset describing the technological and economic parameters of transport technologies and they differ only in terms of transport demand structure, as already explained in Section 3.2 and visible comparing Figs. 1 and 2.

The two model results are compared for the same Baseline scenario, which includes an increasingly stringent bound on CO_2 emissions acting from 2020 up to the end of the time horizon (Table 3).

The elasticity of substitution values adopted for the Baseline scenario σ_k are set equal to - 3 for each *t* and each aggregate *k*. Moreover, for each demand segment, 10 step variables are used to linearize its elastic response in both the up (*n*) and the low direction (*m*), within each *t*. Lastly, elastic substitution is allowed only from 2020 onwards with an increasing potential, as outlined in Section 3.4.

The choice of the policy measure is arbitrary and has the sole scope of stimulating changes in the shadow prices of the transport demand segments in TIMES-DKEMS compared to the reference case. These changes in shadow prices drive the demands elastic responses. Nevertheless, the CO_2 emission-bound trend is obtained from the CO_2 emissions trajectory resulting in [31] when allowing endogenous modal shift in TIMES-DK. This choice is done to facilitate comparison with a similar case study. Reference shadow prices $p^0_{k,i}(t)$ are calculated by letting the model find the optimal solution without the environmental constraint under study and without elastic demand functions, ceteris paribus.

4. Results

This section provides the results of the analysis undertaken to test the use of substitution elasticities to model modal shift in TIMES models. First, Section 4.1 compares the results obtained with TIMES-DK and TIMES-DKEMS for the Baseline scenario. In Section 4.2, a sensitivity analysis is conducted on TIMES-DKEMS to assess how modal substitution is affected by a variation in the assumed elasticities.

4.1. *Elastic modal shift results*

The modal shares determined by TIMES-DKMES in 2050 are compared to the ones exogenously declared in TIMES-DK in Fig. 3. In TIMES-DK the optimal solution is the least-cost fleet of technologies that satisfies the exogenously defined transport demand segments ($DM^0_{k,i}(t)$) for the entire time horizon. On the other hand, in TIMES-DKEMS, the solution is determined as a co-optimization of modal shares and technology shares, providing the model with extra flexibility in the identification of least-cost decarbonisation pathways. TIMES-DKEMS can fulfil the environmental target also shifting part of the mobility demand from one transport mode to another; in particular, this occurs only when this choice is beneficial from a total system cost perspective, resulting in a lower total expenditure for the entire time horizon compared to TIMES-DK.

In TIMES-DKEMS, train, coach, light rail and metro increase their demands compared to their exogenous defined levels (represented by TIMES-DK demand levels) at the expense of car and bus, while the demands of the other modes remain almost constant. In particular, given their travel patterns, coach and train substitute car and bus in the longer distance classes, while light rail and metro in the lower ones. The highest overall contribution to modal shift is due to mode car, whose demand decreases by almost 11% compared to its original level. Car transport is mostly replaced by train and coach, modes with lower levelized costs, which increase their demands by respectively about 96% and 47% compared to TIMES-DK.

Table 1
Modal shift potentials $\Delta^{up,lo}_{k,i}(t)$ for each mode. The adopted potentials are equal across distance range class k. Other modes include: public bus, coach, motorbike, moped, light rail, train, metro, bike and walk. * Long distance demand segments for coach and train have 87% and 86% low potential respectively in 2050.

Year	2020	2050
Car	−25%; +0%	−100%; +0%
Other modes*	−25%; +25%	−100%; +100%

Table 2
Maximum achievable modal shift (Mpkm) in each aggregate k. The total is the sum across the aggregates.

	Aggregate (*k*)	Year	
		2020	2050
Maximum achievable modal shift (*Mpkm*)	XS	637	2617
	S	1102	5542
	M	595	2578
	L	1747	7466
	Total	4081	18,203

Table 3
Bound on CO_2 emissions over the time horizon (Baseline scenario).

Year	2020	2025	2030	2035	2040	2045	2050
CO_2 emission bound (Mtonnes)	10	7.5	6.5	5.8	5	4.5	0

Modal shift is shown in greater detail in Fig. 4, where changes in demands are presented for the entire time horizon in both absolute values and as percentage of maximum achievable modal shift in 2050 (shown in Table 2). Moreover, modal shift is presented separately for each distance range class *k*, and as total (*Tot*) summing up all contributions across classes.

The highest contributor to the overall modal shift (*Tot*) among distance range classes, is represented by the long distance (*L*), which provides the largest response in terms of elastic demands change. The explanation for this behavior is in the magnitude of each demand aggregate *k* defined exogenously. As explained in Section 3, transport demand segments can change their levels only in relation to their exogenous values $DM_{k,i}^{0}(t)$, and by a theoretical maximum change of ± 100%, thus larger demand segments can vary more than smaller demand segments. The long distance aggregate (*L*) covers the largest share of the overall transport demand in Denmark in each year with a 42% share, thus it is also the distance range class responsible for the highest shift in demand. Concerning the other distance range classes *S*, *M* and *XS*, they cover each year 30%, 20% and 8% of the total transport demand respectively. The same merit order is roughly respected also for contributions to the overall modal shift.

The total modal shift increases over the time horizon, covering in 2020 15% of the maximum achievable shift and reaching 44% in 2050. This increasing trend is the result of a combined effect: the increasing relaxation of the shift potential for each demand segment over the time horizon (shown in Table 1), and an increasingly stringent bound on CO_2 emissions over the same period. The only exception to this behavior is identified in the lower distance classes. Within *XS* and *S*, modal shift shows an initial increase culminating in 2025, to which follows a slight decrease. For *XS*, this trend continues until the end of the time horizon, while for *S*, it translates into a plateau. The mentioned trends can be explained considering that the *S* and *XS* distance range classes have the highest concentration of zero-emission modes already in 2020, such as walk, bike and metro (only present in *XS* and *S*) and light rail. For this reason, at the early stage of the time horizon (2020 – 2025), when alternatives with lower carbon emissions are still not fully available for cars, the model fully exploits the availability of such options already accessible for other modes, substituting car demands in *XS* and *S* with walk, bike, metro, light rail and train, until saturating their shift potentials for such years. In the second part of the time horizon, when the CO_2 bound becomes more stringent and clean technologies available in the rest of the distance range classes, modal shift dominates in the longer distance classes.

As expected, modal shift also affects fuel consumption. The evolution of fuel consumption from inland passenger transport sector over the time horizon is provided for the two models in Fig. 5, together with the applied bound on CO_2 emissions. TIMES-DK and TIMES-DKEMS are characterized by similar patterns for total fuel demand and their composition. Fossil fuels are gradually substituted by bio-fuels and electricity, as a result of the increasingly stringent emissions bound (emissions for such energy vectors are not accounted for).

In both the models, the total fuel demand decreases over time,

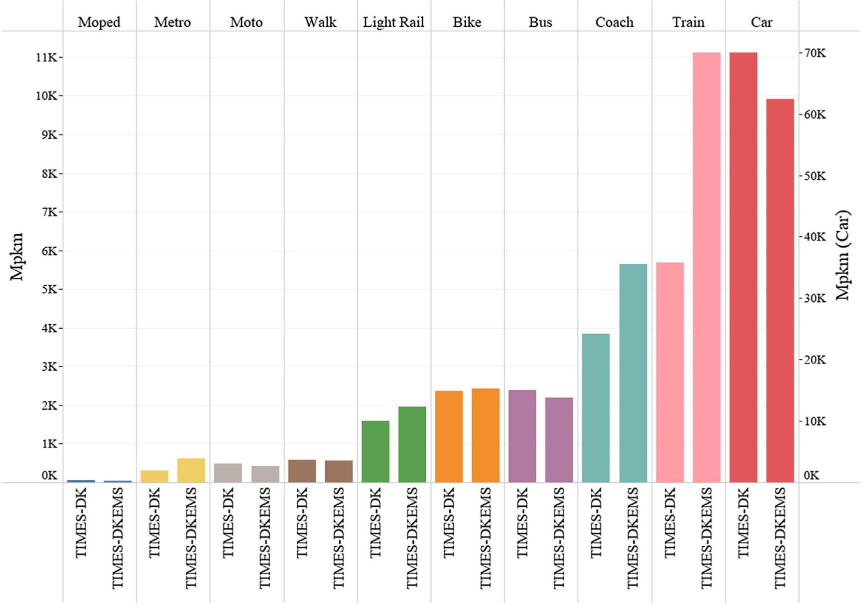


Fig. 3. Comparison of the modal shares in 2050 for TIMES-DK and TIMES-DKEMS.

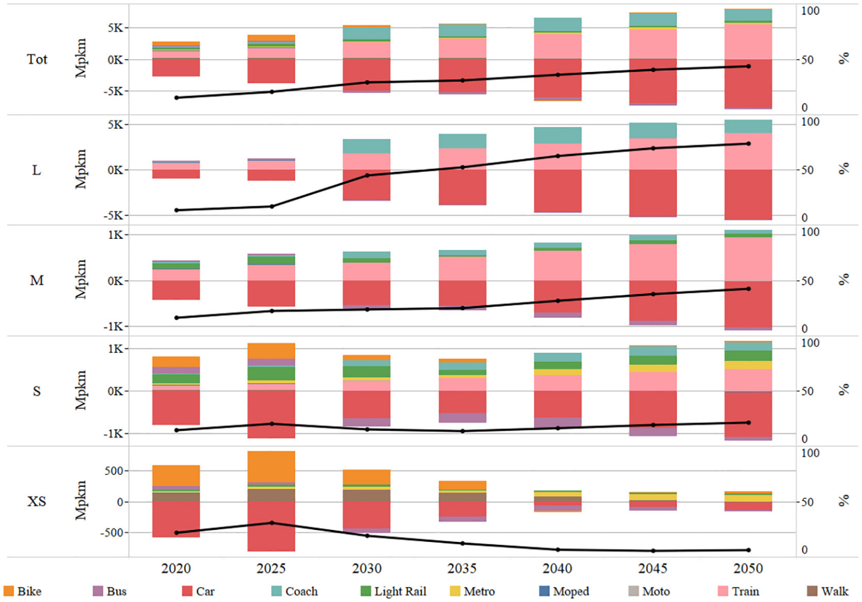


Fig. 4. Modal shift in TIMES-DKEMS.

despite the increasing transport activity. This is due to the combination of increasing fuel economy for new vehicles and a slight electrification of the fleet (electric vehicles have a significantly higher fuel economy than their equivalent internal combustion engines (ICE)). However, the two models show increasing differences in terms of fuel consumption in the period when the environmental constraint is active. In particular, TIMES-DKEMS is characterized every year by a lower final energy demand, which in 2050 accounts for 12 PJ less than TIMES-DK, representing a 12.5% of fuel saving. These differences are attributable to modal shift, which in 2050 occurs mostly away from car towards the more efficient modes, viz., train and coach (Fig. 3).

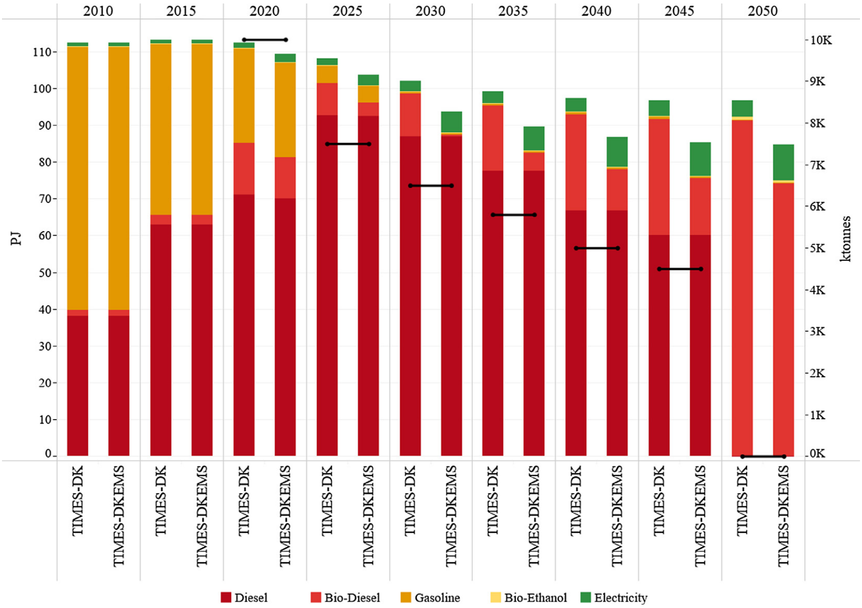


Fig. 5. Fuel consumption in inland passenger transport sector and CO_2 bound for TIMES-DK and TIMES-DKEMS in the Baseline scenario.

4.2. Sensitivity analysis

This section analyses the sensitivity of TIMES-DKEMS to the main parameter involved in regulating the substitution mechanism, which is σ_k, with respect to the Baseline scenario and in terms of modal shift. The value of the substitution elasticity is varied in the range of -1 and -5 and is assumed equal for all the aggregates k and for each year t of the time horizon.

Total modal shift in the inland passenger transport sector resulting from the different values adopted for σ_k is shown in Fig. 6. Across all the different sensitivity cases analyzed, modal substitution dynamics are characterized by a pattern similar to the one already identified and explained for the Baseline case (see Section 4.1). For all the values of σ_k adopted, total modal shift increases steadily over the years. As for the Baseline scenario, this is the result of a combined effect of the increasing emissions bound and the relaxation of shift potentials. The only exception is represented by $\sigma_k = -1$, which shows a higher total modal shift in 2030 compared to 2050. This can be explained considering that 2035 is a model transition year, when most of the clean technologies become available and more competitive for every mode compared to previous years. Thus in 2030, when such options are not yet available, for some modes, the model prefers shifting part of the modal demand, instead of adopting specific modal technologies. This phenomenon is evident only for $\sigma_k = -1$ because, for lower elasticities values, the model is less sensitive to changes in shadow prices, thus, the shift takes place only where such difference is more pronounced, namely in 2030. However, besides this year, the trend is also respected for this case.

Higher absolute values of substitution elasticities result in higher levels of modal shift. This trend is verified for each year and for each σ_k (Fig. 6). This behaviour can be explained by elaborating on Eq. (2), which can be written as in Eq. (6) for each year t:

$$p^{\pm}_{k,ji} = p^0_{k,i}(a_{k,j,i})^{\frac{1}{\sigma_k}} \tag{6}$$

$$\text{where} \quad \begin{cases} a_{k,j,i} > 1 \text{ for } p^{+}_{k,ji} \\ a_{k,j,i} < 1 \text{ for } p^{-}_{k,ji} \end{cases} \quad \forall\ k, \forall\ j, \forall\ i$$

In particular, for every j and every i and for $\sigma_k \in (-\infty, 0)$, $p^{\pm}_{k,ji}$ are monotone functions of σ_k. As shown in Eqs. (7) and (8), $p^{+}_{k,ji}$ is a monotone decreasing function of σ_k limited above by $p^0_{k,i}$ and below by 0, while $p^{-}_{k,ji}$ is a monotone increasing function of σ_k limited below by $p^0_{k,i}$:

$$p^{+}_{k,ji} = \begin{cases} p^0_{k,i} & \text{for } \sigma_k \to -\infty \\ 0 & \text{for } \sigma_k \to 0^- \end{cases} \quad \forall\ k, \forall\ j, \forall\ i \tag{7}$$

$$p^{-}_{k,ji} = \begin{cases} p^0_{k,i} & \text{for } \sigma_k \to -\infty \\ +\infty & \text{for } \sigma_k \to 0^- \end{cases} \quad \forall\ k, \forall\ j, \forall\ i \tag{8}$$

The terms $p^{\pm}_{k,ji}$, are the coefficients of the demand price functions of the increase $(+)$ and decrease $(-)$ step variables that appear in the objective function. In particular, their levels are identified by the model while maximizing the total surplus of consumers and producers in the system. The increase and the decrease of a specific demand segment takes place only when such variation leads to a decrease in the total system cost compared to the inelastic case. This in particular occurs, for the increase, when the price of supplying an additional unit of the i-th demand $(p'_{k,i})$ is lower than $p^{+}_{k,ji}$; for the decrease, when the price of supplying an additional unit of demand i-th $(p'_{k,i})$ is higher than $p^{-}_{k,ji}$. Since for $\sigma_k \to -\infty$, $p^{\pm}_{k,ji}$ tend to $p^0_{k,i}$, higher absolute values of σ_k mean the lower the difference between $p'_{k,i}$ and $p^0_{k,i}$ should be to make the demand increase and decrease beneficial from a total system cost point of view. Thus, ceteris paribus, increasing σ_k in their absolute values is equivalent to making the model more sensitive to differences between the $p'_{k,i}$ and $p^0_{k,i}$.

In addition, higher j corresponds to higher $p^{-}_{k,ji}$ and lower $p^{+}_{k,ji}$. This means that for higher j, higher differences in shadow prices are needed to trigger a demand change. For this reason, the optimization guarantees that step variables are increased/decreased consecutively and in

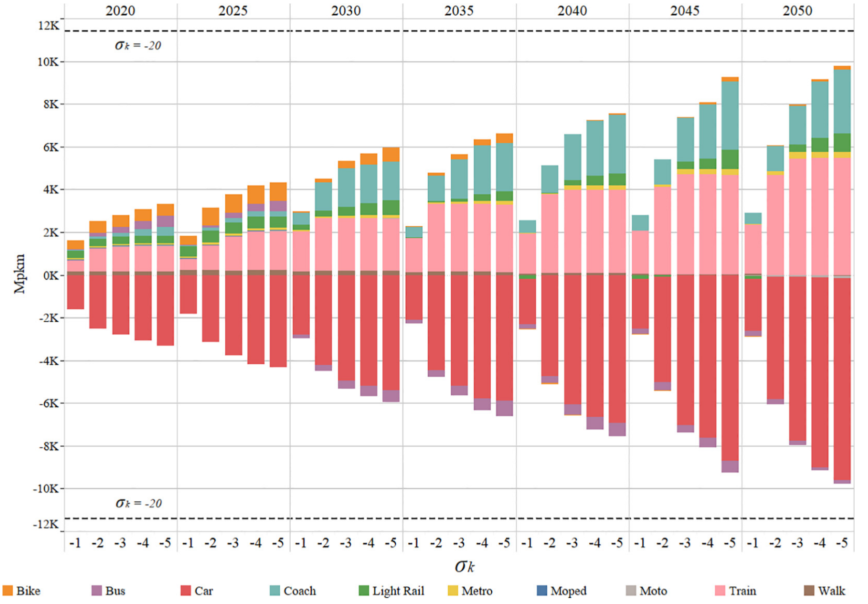


Fig. 6. Total modal shift over the time horizon for different sensitivity cases. Dashed lines represent total modal shift for $\sigma_k = -20$.

the correct order [42]. Thus, higher absolute values of σ_k can lead to more step variables being involved in elastic demand response to price change, resulting in a higher demand shift.

On the other hand, the volume preserving condition (Eq. (4)), which forces the net total modal shift to be zero within each aggregate, directly affects the substitution dynamic. Demand segments whose shadow prices have changed enough to stimulate an elastic price demand response, can vary their levels only if other demand components defined in the aggregate vary by the same quantity but in the opposite direction. This can lead, for example, to situations where demand segments increase their levels only to accommodate variations of other demand segments, even though their shadow prices have remained unchanged or have even increased compared to the reference case, representing an additional cost for the system and thus reducing the overall benefit gained by adjusting the other demands in the aggregate. Nevertheless, the overall demand adjustments in an aggregate always bring to an overall increase in the maximized total surplus of consumers and producers compared to the inelastic case.

Total modal shift in 2050 never reaches its maximum achievable (18,203 Mpkm, Table 2, Section 3.4), but it saturates asymptotically around 11,500 Mpkm (obtained with $\sigma_k = -20$) (dashed lines in Fig. 6). This can be explained considering the interaction between the substitution mechanism and the travel patterns, which results in a distortion of the elastic demand response dynamic explained above. Technologies defined in a specific mode are constrained to satisfy a given travel pattern (see Section 3). Moreover, exogenous modal demand segments $DM^0_{k,i}(t)$ across distance range classes follow the same proportions as those outlined by the modal travel pattern. Thus, a modal demand segment variation in a specific distance range class k leads to a different proportion among the demand segments compared to the original one. This results in an impossibility for the marginal modal technology to satisfy the demand variation, unless the variation is counterbalanced by changes (in the same direction) of the other modal demand segments in the other classes k, in such a way that their proportions remain constant and equal to the modal travel pattern. However, travel patterns are relaxed by 2% compared to the BY from 2012 onwards, softening this effect.

This latter dynamic hampers modal shift, which saturates asymptotically around 11,500 Mpkm. After this value, with the set of reference shadow prices $p^0_{k,i}(t)$, and with the specific environmental policy adopted, the model does not gain any ulterior benefit in shifting additional travel demand across the modes, even for higher elasticity values.

5. Discussion and future research

TIMES-DKEMS uses substitution elasticities to model passenger transport modal shift within BU optimization E4 energy system models. Integrating modal shift within energy system models allows to better identify efficient policy mechanisms triggering modal shift towards low-carbon transport modes. The proposed methodology presents a major advantage compared to other approaches aimed at representing the same phenomenon in this type of models, such as [31,32,34]. The data requirement is limited and consists mainly of the identification of the substitution elasticities for the distance range classes σ_k, and of the modal shift potentials $\Delta^{up,lo}_{k,i}(t)$. Contrary to [31,34], the methodology proposed relies only to a minor extent on national travel surveys, while the external support of national transport simulation models is not required. In particular, findings based on the TU survey are used in TIMES-DKEMS only for the identification of modal shift potentials and modal travel patterns. The low data requirement is also reflected by a simple modelling structure (evident from the comparison of Figs. 1 and 2), which relies only on the use of a standard set-up outlined in [40] that avoids the definition of ulterior constraints and makes the modelling structure straightforward and compact. However, this study did not account for transport infrastructure, like road and rail networks, which are necessary requirements to accommodate travel demand. In particular, modal shift could be limited by infrastructure saturation as considered by [31]. The inclusion of such aspect in TIMES-DKEMS would lead to a more complex modelling structure than the one outlined.

The major drawback of using substitution elasticities for simulating modal shift is the severe simplification of the addressed phenomenon. In reality, consumer modal choice is driven by multiple factors, such as level of service (LoS) parameters like travel time, travel cost and travel comfort, which characterise every mode differently. Moreover, consumers belonging to different socio-economic and demographic groups (age, gender, income, etc.) evaluate those factors differently, when making transport choices [34]. In the proposed methodology, all these dynamics are reduced to the values adopted for σ_k. In addition, the magnitude of modal shift achievable with the methodology hereby presented is limited by its mathematical formulation. In particular, each demand $DM_{k,i}(t)$ can increase or decrease its level by a certain percentage $\Delta^{up,lo}_{k,i}(t)$ (referred to $DM^0_{k,i}(t)$). This limits the applicability of the methodology only to such cases where modal shift can occur within a 100% change relative to the original travel demands.

The results obtained from TIMES-DKEMS in the Baseline scenario show a similar magnitude and pattern of modal shift as the results obtained in [31]. However, the values of σ_k adopted in this study are arbitrary and have the sole aim of illustrating the novel methodology proposed. For the Baseline scenario, the values of σ_k were chosen in the light of the sensitivity analyses carried out on σ_k. In particular, for $\sigma_k = -3$ the modal shift magnitude obtained is well below the saturation level observed for higher values, and offers a satisfying demand response to changes in the shadow prices obtained with the specific environmental policy applied.

The identification of proper values for σ_k is the main challenge for the utilization of elasticities of substitution to simulate modal shift. Transport price elasticities available in the literature, such as those from transport simulation models, cannot be used directly in the novel modelling framework. The reason is that the values of substitution elasticities adopted should always be consistent with the travel costs defined in the model. In TIMES-DKEMS, travel costs for private and public transport modes include annualized investment cost, operation and maintenance (O&M) cost and fuel cost. Instead, transport elasticities available in the literature are usually estimated with respect to different types of costs, which do include O&M costs and fuel cost but could also include, for example, parking fee or road toll for private modes [44,45] and transit fare for public transport [46,47]. Given such differences in travel cost definition, the direct use of transport elasticity values from the literature in TIMES-DKEMS seems a major challenge.

Results shown in Section 4.1 are obtained using the same arbitrary elasticity of substitution σ_k for every aggregate k and for the whole time horizon T. Nevertheless, the proposed methodology theoretically allows to differentiate the substitution elasticities across distance-range classes and over time. Moreover, transport price elasticities (such as cross-price elasticities and direct price elasticities) can vary according to trip lengths, as those identified by [46]. Besides, elasticities can also be differentiated with respect to the duration of the response period analyzed, namely short-term and long-term [44,48]. Therefore, future research for the improvement of this methodology will consist of implementing values for the substitution elasticities representative for a real case study and differentiated by distance-range classes and possibly by t. Moreover, a characterization of σ_k for every mode i in each aggregate k is theoretically possible with the elastic demand formulations available in TIMES models [40]. This set-up, allowing capturing differences in elastic price response for different modes, could also be tested.

Modal travel patterns tend to hamper the modal shift resulting from the elastic substitution mechanism (Section 4.2). However, travel patterns are included in the model in order to represent modal travel habits, thus, a full exclusion of such constraints would lead to an unrealistic adoption of transport modes with respect to the distance range classes *k*. Further research should focus on how more flexible travel patterns than those assumed in this study influence modal shift saturation within TIMES-DKEMS.

Finally, an interesting application of the proposed methodology would be the description of the freight transport modal shift, which is by nature more governed by cost minimization, rather than behavioral aspects. Moreover, the methodology adopted in this study could be applied to describe other phenomena than transport modal shift, where demand substitutions take place with similar dynamics. Additionally, TIMES models offer different variants for substitution elasticities to the volume-preserving assumption used in this study [40], and these can be used for best describing case-specific phenomena.

6. Conclusions

This study presents TIMES-DKEMS, a novel methodology that adopts elasticities of substitution to simulate transport passenger modal shift in TIMES (The Integrated MARKAL-EFOM System) models. Incorporating endogenous modal shift in energy system models enables the assessment of more effective policies encouraging the transition to a fossil-free transport sector, by identifying their interactions with the whole energy system. This is particularly relevant, considering that transport is expected to become increasingly integrated with the rest of the energy system in the future.

The methodology adopted in TIMES-DKEMS is described in detail and tested for an environmental policy stimulating changes in the shadow prices that drive the elastic modal shift. The results show a demand shift towards the more efficient and less carbon-intense modes defined, increasing over the time horizon as result of the increasingly stringent policy and the increasing shift potentials. Moreover, a sensitivity analysis on the values of the substitution elasticities reveals that higher absolute values of elasticities entail higher modal shift, despite the maximum modal shift potential not being reached. To the contrary, modal shift saturates asymptotically due to the interactions between the substitution mechanism and other model constraints such as the imposition of dedicated travel patterns for the different modes.

The modelling structure is simple and compact, and does not require ulterior constraints definitions in the model. The data requirement is limited to the characterization of the substitution elasticities for each aggregate and of the shift potentials for each demand participating in the elastic response. The main drawback of this methodology consists in the rather simplified representation of modal shift, since all factors driving modal choice in reality are reduced to the values adopted for the substitution elasticities. Moreover, the identification of proper values of elasticities to be adopted seems challenging, considering that transport price elasticities existing in the literature usually account for travel costs different from those usually included in TIMES models. Thus, the authors identify as further research the identification and adoption of substitution elasticities values representative for a real case study, differentiated by distance-range classes, possibly over the time horizon and by mode.

Lastly, the proposed methodology, with the proper adaptations, could be applied in TIMES models to describe phenomena other than transport modal shift, where a demand substitution takes place with similar dynamics.

Acknowledgments

The work presented in this paper is a result of the research activities of the COMETS (Co-Management of Energy and Transport Sector) project (grant number 4106-00033A) and the SHIFT (Sustainable Horizons for Transport) project (grant number 77892), funded respectively by The Innovation Fund Denmark, and Nordic Energy Research. Raffaele Salvucci is grateful to Professor Stefano Corgnati and Professor Romano Borchiellini for the opportunity to spend a visiting research period at the Energy Center of the Politecnico di Torino, during which the draft of the present manuscript was prepared and which was possible thanks to the financial support of the Otto Mønsteds Fond.

References

[1] Sims R, Schaeffer R, Creutzig F, Cruz-Núñez X, D'Agosto M, Dimitriu D, et al. Transport climate change 2014: mitigation of climate change. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, editors. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2014.
[2] International Energy Agency. Energy Technology Perspectives 2016. Paris, France; 2016.
[3] International Energy Agency. Transport, Energy and CO2. Paris, France; 2009.
[4] Roskilly AP, Palacin R, Yan J. Novel technologies and strategies for clean transport systems. Appl Energy 2015;157:563–6. https://doi.org/10.1016/j.apenergy.2015.09.051.
[5] International Energy Agency. Nordic EV Outlook 2018. Paris, France; 2018.
[6] International Energy Agency. The Future of Trucks. Paris, France; 2017.
[7] International Energy Agency. Energy Technology Perspectives 2015. Paris, France; 2015.
[8] Schwanen T, Banister D, Anable J. Scientific research about climate change mitigation in transport: a critical review. Transp Res Part A Policy Pract 2011;45:993–1006.
[9] Chiodi A, Gargiulo M, Rogan F, Deane JP, Lavigne D, Rout UK, et al. Modelling the impacts of challenging 2050 European climate mitigation targets on Ireland's energy system. Energy Policy 2013;53:169–89. https://doi.org/10.1016/j.enpol.2012.10.045.
[10] Yang C, Yeh S, Zakerinia S, Ramea K, McCollum D. Achieving California's 80% greenhouse gas reduction target in 2050: technology, policy and scenario analysis using CA-TIMES energy economic systems model. Energy Policy 2015;77:118–30. https://doi.org/10.1016/j.enpol.2014.12.006.
[11] McCollum D, Yang C, Yeh S, Ogden J. Deep greenhouse gas reduction scenarios for California – Strategic implications from the CA-TIMES energy-economic systems model. Energy Strateg Rev 2012;1:19–32. https://doi.org/10.1016/j.esr.2011.12.003.
[12] Bahn O, Marcy M, Vaillancourt K, Waaub J-P. Electrification of the Canadian road transportation sector: A 2050 outlook with TIMES-Canada. Energy Policy 2013;62:593–606. https://doi.org/10.1016/j.enpol.2013.07.023.
[13] Zhang H, Chen W, Huang W. TIMES modelling of transport sector in China and USA: Comparisons from a decarbonization perspective. Appl Energy 2016;162:1505–14. https://doi.org/10.1016/j.apenergy.2015.08.124.
[14] Føyn THY, Karlsson K, Balyk O. Grohnheit PE. A global renewable energy system: a modelling exercise in ETSAP/TIAM. Appl Energy 2011;88(2):526–34. https://doi.org/10.1016/j.apenergy.2010.05.003.
[15] Venturini G, Tattini J, Mulholland E. Ó Gallachóir B. Improvements in the representation of behaviour in integrated energy and transport models. Int J Sust Transp 2018. https://doi.org/10.1080/15568318.2018.1466220.
[16] Schäfer A. Introducing behavioral change in transportation into energy/economy/environment models. Policy research working paper no. WPS 6234. Washington, DC: World Bank; 2012.
[17] DeCarolis J, Daly H, Dodds P, Keppo I, Li F, McDowall W, et al. Formalizing best practice for energy system optimization modelling. Appl Energy 2017;194:184–98. https://doi.org/10.1016/j.apenergy.2017.03.001.
[18] Train K. Qualitative choice analysis – Theory, econometrics and application to automobile demand. The MIT Press; 1986.
[19] Domencich T, McFadden D. Urban travel demand - a behavioral analysis. Amsterdam: North Holland Publishing Co.; 1975.
[20] Ben-Akiva M, Lerman SR. Discrete choice analysis – Theory and application to travel demand. The MIT Press; 1985.
[21] National Transport Authority. Regional Modelling System – Full demand model specification report. Dublin, Ireland; 2017.
[22] Cambridge Systematics. California Statewide Travel Demand Model, Version 2.0 - Model Overview - Final Report. Oakland, CA, USA; 2014.
[23] Sillaparcharn P. National transport demand modelling - general approach and application to Thailand. Leeds, UK; 2007.
[24] Karplus VJ, Paltsev S, Babiker M, Reilly JM. Applying engineering and fleet detail to represent passenger vehicle transport in a computable general equilibrium model. Econ Model 2013;30:295–305. https://doi.org/10.1016/j.econmod.2012.08.019.
[25] Pietzcker R, Moll R, Bauer N, Luderer G. Vehicle technologies and shifts in modal split as mitigation options towards a 2 °C climate target. In: Int Soc Ecol Econ 11th Bienn Conf, Oldernburg; 2010.
[26] Horne M, Jaccard M, Tiedemann K. Improving behavioral realism in hybrid energy-economy models using discrete choice studies of personal transportation decisions. Energy Econ 2005;27:59–77. https://doi.org/10.1016/j.eneco.2004.11.003.
[27] E3MLab/ICCS at National Technical University of Athens. PRIMES-TREMOVE Transport Model, Detailed model description. Athens, Greece; 2014.
[28] Girod B, van Vuuren DP, Deetman S. Global travel within the 2°C climate target. Energy Policy 2012;45:152–66. https://doi.org/10.1016/j.enpol.2012.02.008.
[29] McCollum DL, Wilson C, Pettifor H, Ramea K, Krey V, Riahi K, et al. Improving the behavioral realism of global integrated assessment models: An application to consumers' vehicle choices. Transp Res Part D Transp Environ 2017;55:322–42. https://doi.org/10.1016/j.trd.2016.04.003.

[30] Brand C, Tran M, Anable J. The UK transport carbon model: An integrated life cycle approach to explore low carbon futures. Energy Policy 2012;41:107–24. https://doi.org/10.1016/j.enpol.2010.08.019.

[31] Tattini J, Gargiulo M, Karlsson K. Reaching carbon neutral transport sector in Denmark – Evidence from the incorporation of modal shift into the TIMES energy system modeling framework. Energy Policy 2018;113:571–83. https://doi.org/10.1016/j.enpol.2017.11.013.

[32] Daly H, Ramea K, Chiodi A, Yeh S, Gargiulo M, Gallachóir BP. Incorporating travel behaviour and travel time into TIMES energy system models. Appl Energy 2014;135:429–39. https://doi.org/10.1016/j.apenergy.2014.08.051.

[33] Pye S, Daly H. Modelling sustainable urban travel in a whole systems energy model. Appl Energy 2015;159:97–107. https://doi.org/10.1016/j.apenergy.2015.08.127.

[34] Tattini J, Ramea K, Gargiulo M, Yang C, Mulholland E, Yeh S, et al. Improving the representation of modal choice into bottom-up optimization energy system models – The MoCho-TIMES model. Appl Energy 2018;212:265–82. https://doi.org/10.1016/j.apenergy.2017.12.050.

[35] Cayla JM, Maïzi N. Integrating household behaviour and heterogeneity into the TIMES-Households model. Appl Energy 2015;139:56–67. https://doi.org/10.1016/j.apenergy.2014.11.015.

[36] Duarte R, Feng K, Hubacek K, Sánchez-Chóliz J, Sarasa C, Sun L. Modeling the carbon consequences of pro-environmental consumer behavior. Appl Energy 2016;184:1207–16. https://doi.org/10.1016/j.apenergy.2015.09.101.

[37] Liu X, Bohlin L. Effects from consistent internalization of external effects from transport and manufacturing – a CGE analysis for Sweden. Örebro, Sweden; 2012.

[38] Waisman HD, Guivarch C, Lecocq F. The transportation sector and low-carbon growth pathways: modelling urban, infrastructure, and spatial determinants of mobility. Climate Policy 2013;13:106–29. https://doi.org/10.1080/14693062.2012.735916.

[39] Delhaye E, Breemersch T, Vanherle K, Kehoe J, Liddane M, Riordan K. COMPASS The COMPetitiveness of EuropeAn Short-sea freight Shipping compared with road and rail transport - Final Report. Belgium; 2010.

[40] Lehtilä A. TIMES Micro – Elastic Demand Functions. Energy Systems Technology Analysis Programme (ETSAP). International Energy Agency (IEA); 2018. https://iea-etsap.org/docs/TIMES-Micro-Note.pdf [accessed 05.07.18].

[41] Petrovic S, Karlsson K. Residential heat pumps in the future Danish energy system. Energy 2016;114:787–97. https://doi.org/10.1016/j.energy.2016.08.007.

[42] Loulou R, Goldstein G, Kanudia A, Lehtilä A, Remme U. Documentation for the TIMES Model - Part I: TIMES concepts and theory. Energy Systems Technology Analysis Programme (ETSAP). International Energy Agency (IEA); 2016. https://iea-etsap.org/docs/Documentation_for_the_TIMES_Model-Part-I_July-2016.pdf. [accessed 05.07.18].

[43] DTU Transport. Danish National Travel Survey - dataset TU0615v1 from May 2006 to December 2015; 2016 [accessed 10.09.17].

[44] Litman TA. Understanding transport demands and elasticities: how prices and other factors affect travel behavior. Victoria, British Columbia, Canada; 2017.

[45] Fearnley N, Flügel S, Killi M, Gregersen FA, Wardman M, Caspersern E, et al. Triggers of Urban Passenger Mode Shift – State of the Art and Model Evidence. Transp Res Procedia 2017;26:62–80. https://doi.org/10.1016/j.trpro.2017.07.009.

[46] Rich J. The Weekday Demand Model in LTM – Model For Generation, Destination and Mode Choice. Kgs. Lyngby, Denmark; 2015.

[47] Fearnley N, Currie G, Flügel S, Gregersen FA, Killi M, Toner J, et al. Competition and substitution between public transport modes. ResTransp Econ 2018:1–8. https://doi.org/10.1016/j.retrec.2018.05.005.

[48] Goodwin P, Dargay J, Hanly M. Elasticities of Road Traffic and Fuel Consumption with Respect to Price and Income: A Review. Transp Rev 2004;24:275–92. https://doi.org/10.1080/0144164042000181725.

Paper **IV**

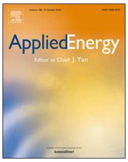
The role of modal shift in decarbonising the Scandinavian transport sector: Applying substitution elasticities in TIMES-Nordic

Applied Energy 253 (2019) 113593

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy



The role of modal shift in decarbonising the Scandinavian transport sector: Applying substitution elasticities in TIMES-Nordic

Raffaele Salvucci[a,*], Maurizio Gargiulo[b], Kenneth Karlsson[a]

[a] *Technical University of Denmark, Department of Management Engineering, Produktionstorvet, Building 424, 2800 Kgs. Lyngby, Denmark*
[b] *E4SMA S.r.l., Via Livorno 60, 10144 Turin, Italy*

HIGHLIGHTS

- Model passenger and freight elastic modal shift in TIMES energy system models.
- Substitution elasticities characterize modal substitution across distance classes.
- Long-term own-price transport elasticities are adopted from the literature.
- Modal shift is cost-effective for decarbonising the Scandinavian transport sector.
- Modal competition requires a well-balanced technology description among modes.

ARTICLE INFO

Keywords:
Energy system models
Low-carbon transition
Scenario analysis
Sustainable mobility
Transport elasticities

ABSTRACT

In the Nordics, transportation accounts for almost 40% of energy-related CO_2 emissions, a higher share than most European countries. The International Energy Agency identifies modal shift as pivotal for a sustainable transition of the transport sector. This study analyses the role of modal shift in the decarbonisation of the Scandinavian energy system with TIMES-Nordic, the TIMES (The Integrated MARKAL-EFOM System) model depicting the national energy systems of Denmark, Norway and Sweden. For the first time, passenger and freight modal shift is modelled through substitution elasticities for a real case study. Transport elasticities from the literature are discussed in light of the modelling environment, and long-term direct elasticities are identified as suitable for the purpose. The results obtained with TIMES-Nordic and its version equipped with modal shift are compared under an increasing CO_2 tax. For passenger, car is mainly substituted by rail and non-motorised modes, while for freight, rail replaces truck and ship. Modal shift results in a cost-effective mitigation measure, responsible for 26 PJ of lower fuel consumption in 2050, and 2.2% lower cumulative CO_2 emissions from transport. A sensitivity analysis on the investment costs for electric cars reveals the ineffectiveness of the CO_2 tax in stimulating car substitution in a future where electric cars are more competitive and the power sector almost decarbonised. Estimates of modal shift potentials from alternative methodologies are comparable to the results obtained, highlighting the methodology solidity. Lastly, a well-balanced technology characterization among modes is identified as crucial when enabling modal shift.

1. Introduction

The transport sector is responsible for approximately 28% of total final energy use and for 23% of global energy-related CO_2 emissions [1]. In the baseline scenario of the Energy Technology Perspectives (ETP), the International Energy Agency (IEA) estimated that by 2050 global transport energy demand will increase by 75%, with a concomitant doubling of associated CO_2 emissions [2]. Low-carbon transport technologies are already available in the market, but the high costs hampering their widespread adoption calls for policy support [3]. Countries have announced policy ambitions and commitments in their Nationally Determined Contributions under the Paris Agreement, but these mitigation measures are far from sufficient to limit the average increase in temperature to “well below 2 degrees” above pre-industrial levels, as assessed by [4] and reflected in the New Policy Scenario outlined by the IEA [5]. In the Nordics, transportation accounts for almost 40% of energy-related CO_2 emissions [6], representing a higher share than most other European countries. However, so far the Nordics

---

[*] Corresponding author.
E-mail address: rafs@dtu.dk (R. Salvucci).

https://doi.org/10.1016/j.apenergy.2019.113593
Received 11 February 2019; Received in revised form 19 May 2019; Accepted 19 July 2019

have demonstrated great commitment to decarbonising the power and heat sector and have pioneered the rolling out of aggressive policies supporting, for example, electrical vehicles (EVs) [7]. For the Nordic countries, this represents a significant potential for transformation, as well as being an opportunity to lead the European energy transition and eventually to help other countries meet their targets [3].

Several future scenario analyses addressing the transition towards a low-carbon transport sector have been carried out for Denmark [8], Norway [9] and Sweden [10,11]. However, the Scandinavian region as a whole has been addressed in just a few studies. The Nordic Energy Technology Perspectives (NETP) 2013 [12] and 2016 [6] provide a detailed scenario analysis of how the Nordic countries can achieve a near carbon-neutral energy system by 2050. Similar studies have been carried out by [13] for the Nordic region (excluding Iceland) and by [14] for Scandinavia. Other studies are limited to the investigation of the role of a specific transport technology within the Nordic context. For instance, [15] and [16] study the effect of a wide penetration of electric vehicles in Northern Europe. Approaching the Scandinavian region as a whole enables the identification of potential solution synergies across countries [17]. TIMES-Nordic, a novel TIMES (The Integrated MARKAL-EFOM System) model covering the full energy system of Denmark, Norway and Sweden, is applied in this study to explore the role of modal shift in decarbonising the Scandinavian transport sector.

In order to facilitate a holistic perspective, the transport sector can be modelled within energy system models, which are comprehensive tools for supporting energy future scenario analyses. In particular, TIMES models, belonging to the category of energy-economy-environmental-engineering (E4) optimization models, have been used for almost four decades to identify least-cost technology pathways while meeting national environmental targets. E4 optimization models rely on a thorough technology description, though they are still weak in depicting transport behavioural aspects [18], such as those driving modal shift [19]. This weakness may not allow the IEA's suggestions for decarbonising the transport sector to be depicted in full, including behavioural and technological measures to be promoted concurrently [20]. In particular, reducing travel demand, supporting modal shift, improving vehicle efficiency and switching to low-carbon fuels are considered pivotal actions [21], making behaviour central to achieving a low-carbon transportation sector. Although behaviour only plays a limited role in freight transportation compared to passenger, these actions are also relevant within the former sector. In fact, the European Commission included freight modal shift among the ten main goals to be pursued by 2030 in its White Paper [22].

Several efforts have been directed at representing competition between transport modes in bottom-up (BU) optimization models to enable modal shift analysis. One approach consists of broadening the classic modelling framework to integrate new transport-specific variables and dimensions such as travel time budget and transport infrastructure. This has been applied for Denmark [23], California and Ireland [24], and the United Kingdom [25]. A second approach involves the inclusion of modal levels of service and consumers' decisions in the modelling framework as done by [26] for France and by [27] for Denmark. These methods tend to increase the model's complexity and its data requirements, relying typically on national travel surveys and external transport simulation models, tools not always within the reach of energy researchers. In addition, to the authors' knowledge, the methodologies just mentioned have only been used to enhance the passenger transport description in E4 models, while the same modelling efforts have not yet been directed to enrich the description of freight transport.

The purpose of this study is to assess the role of transport modal shift for both freight and passenger in the decarbonisation of the Scandinavian transport sector, and to explore the effect of integrating transport modal shift in specific model context. For the first time, transport modal shift is modelled through the use of substitution elasticities in a real case study. This methodology requires only a minimal amount of data and fewer modelling efforts compared to alternative methods [28], characteristics that can be preferable in models with a broad geographical scope, such TIMES-Nordic. The role of transport modal shift up to 2050 is analysed within the context of the Carbon Neutral Scenario (CNS) outlined by [6].

Section 2 describes TIMES-Nordic and the methodology applied, and presents the criteria adopted in selecting appropriate transport elasticities from the literature. Section 3 presents the results together with two sensitivity analyses. Section 4 provides a discussion and further perspectives, while Section 5 concludes the paper.

2. Methodology

The approach adopted in TIMES-Nordic to carry out future scenario analyses on transport modal shift for the Scandinavian region relies on the methodology developed by [28] using elasticities of substitution. A description of TIMES-Nordic is presented in Section 2.1. Section 2.2 describes the structure of TIMES-Nordic transport sector, while Section 2.3 illustrates the elastic modal shift implementation. Section 2.4 describes the identification of suitable transport elasticities in the literature in order to model modal shift and the main assumptions adopted. Lastly, Section 2.5 describes the Base scenario.

2.1. TIMES-Nordic

TIMES-Nordic belongs to the TIMES models family. The TIMES model generator is developed and maintained by the Energy Technology Systems Analysis Programme (ETSAP) [29], an IEA Technology Collaboration Programme. TIMES models are BU partial-equilibrium energy system models that assume perfectly competitive markets and full foresight. TIMES models are suitable for medium or long-term future scenario analyses of energy systems ranging from the city level [30] to the national and global levels [31]. TIMES models optimize investments in technologies and their operations over the defined time horizon by minimizing total system costs, while satisfying the exogenous energy service demand curves and respecting user-defined constraints such as environmental targets, resource availability and policy restrictions. Typical inputs to TIMES models are energy service demand and supply curves and the techno-economic parameters of technologies represented, while outputs range from technology investments and operation levels, energy commodities marginal prices to CO_2 emissions and system costs. More information on TIMES models is provided by [32].

TIMES-Nordic is a multi-country model including Denmark, Norway and Sweden. Each country is geographically aggregated into different regions, as shown in Fig. 1. For Denmark and Sweden model regions correspond to the Nord Pool power regions, while for Norway power regions are aggregated into two macro-regions: NO1 (South) and NO2 (North). Regions are interconnected through the representation of transmission lines, allowing electricity trade. The modelling structure of each national energy system replicates the structure of TIMES-DK, the TIMES model representing the Danish energy system [33]. The whole national energy system is divided into five sectors: supply, power and heat, industry, residential and transport. Some of the sector descriptions vary across countries due to major differences in the respective national economies. For instance, for Norway and Sweden, the "Iron and Steel", "Aluminium", "Pulp and Paper" and "Mining" industrial sectors are added respect to the original structure of TIMES-DK. TIMES-Nordic is calibrated for the base year (BY) 2010 and has techno-economic projections until 2050. The whole time horizon is composed of periods of various length, usually between one and ten years. Moreover, every year is sub-divided into 32 consequential time slices representing seasonal (four seasons), weekly (working/non-working days) and daily variations.

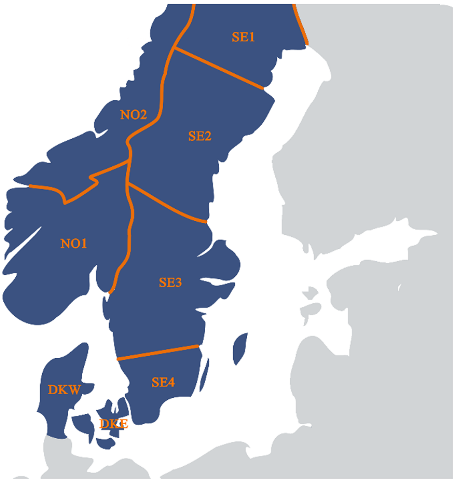


Fig. 1. Model regions in TIMES-Nordic. Modified from [34].

2.2. TIMES-Nordic transport sector

In TIMES-Nordic, each national transport sector comprises passenger and freight transportation, both characterised in terms of mobility demands, end-use transport technologies and fuel chains. Fuels can either be traded in the international market or produced by refineries and bio-refineries. The combustion of biofuels is assumed carbon-neutral, while their domestic production explicitly accounts for the use of primary inputs, such as electricity and biomass. However, except for electricity, fuel transportation and distribution are not modelled.

Each sector is divided into inland, aviation and navigation. Inland passenger transportation comprises ten modes: car, bus, coach, rail (metro, train, light rail), two-wheelers (motorcycle and moped) and non-motorized modes (bike and walk), while the inland freight sector comprises three modes: van, truck and rail. The respective mobility service demands are defined exogenously for each mode for the whole time horizon in the form of passenger-kilometres (pkm) and tonne-kilometres (tkm). In addition, modal demands are split further into distance range classes. For the inland passenger, these are extra short (*XS*, < 5 km), short (*S*, 5–25 km), medium (*M*, 25–50 km) and long (*L*, > 50 km) as described by [28], while for freight they are national short (*NS*, < 50 km), national long (*NL*, > 50 km) and international (*I*). For inland freight modes, the latter class includes only that portion of international transport demand that occurs within the national borders, while for international freight shipping this demand is estimated based on the international bunker consumption as reported by national energy statistics (such as [35]), thus it includes also transport performance outside the national borders. Moreover, for rail and shipping, national demand segments are not split further into short and long.

Each transport mode is characterised by an exogenously defined travel pattern (TP), a constraint defining the percentages travelled in the different distance classes. In the case of passenger transport, TPs reflect population travel habits, while for freight they represent typical modal adoption with respect to distance. TPs are country-specific quantities, which can also vary across regions. The TPs adopted in this study for each region are presented in Table A1 (Appendix A).

For each mode, a set of existing and future technologies is defined. These technologies differ in terms of fuel use, efficiencies and costs, though technical features such as mileage, average occupancy rates and load capacities are mainly assumed to be equal within the same mode. Modal technical features are estimated in the BY based on aggregated national transport statistics, and are adjusted through model calibration. Therefore, for a specific country, modal technical features are representative of the existing national vehicle fleet composing that mode. For instance, one technology is defined respectively for national and international freight ships, whose technical features are representative of a varied fleet mix including, for example, cargo, bulk carriers, roll-on/roll-off and lift-on/lift-off ships.

TIMES satisfies the defined modal demands by deploying the technology mix with the lowest levelised costs while fulfilling the ulterior constraints implemented. Competition among transport technologies occurs only within modes, not across them. More information on the transport structure adopted in TIMES-Nordic is available from [33].

2.3. TIMES-Nordic transport sector equipped with elastic modal shift

Modal shift is enabled in the inland passenger and freight sectors through the use of elastic demand functions applying the methodology developed by [28]. Figs. 2 and 3, show the inland passenger and freight transportation sectors equipped with modal shift:

In every region, and for a specific year *t*, each distance range class *k* (where $k = XS, S, M, L, NL, I$) represents an aggregate, where all corresponding modal demand segments $DM_{k,i}(t)$ (where *i* identifies the mode) are grouped together and a common elasticity of substitution σ_k is defined. Modal demand segments, composing an aggregate *k*, can endogenously adjust their levels in response to changes in their shadow prices compared to a reference case (superscript *0*). The linearization of the demand elastic response in TIMES models is achieved through the inclusion of two sets of step variables (indexed by *j*, Eq. (1)) that are used to rearrange the demand level in response to elastic price changes [36]:

$$DM_{k,i}(t) = DM^{0}_{k,i}(t) - \sum_{j=1}^{m} sm_{k,j,i}(t) + \sum_{j=1}^{n} sn_{k,j,i}(t) \tag{1}$$

Each modal demand segment variation is bounded by the user declaring the maximum allowed percentage change upwards and downwards ($\Delta^{up,lo}_{k,i}$) relative to $DM^{0}_{k,i}(t)$. Each step variable is consequently bounded between zero and a width $\beta_{k,i}(t)$, whose level is identified by the declaration of the linearization steps (*n* and *m*). The step variable demand price functions are included in the objective function, whose coefficients are expressed by Eq. (2) [36], where $p^{0}_{k,i}(t)$ represents the shadow price obtained from the reference case:

$$p^{\pm}_{k,ji}(t) = p^{0}_{k,i}(t)\left(\frac{DM^{0}_{k,i}(t) \pm \left(j - \frac{1}{2}\right)\cdot\beta_{k,i}(t)}{DM^{0}_{k,i}(t)}\right)^{\frac{1}{\sigma_k}} \tag{2}$$

Moreover, the total volume of each aggregate *k* is constrained to be conserved after substitution (volume-preserving condition [36]), assuming that each mode is a perfect substitute of the others. Demand shifts across modes only occur when they are beneficial from a total system cost perspective, resulting in a lower total expenditure for the entire time horizon compared to the inelastic case.

For passenger, only inland modes participate in modal shift, while for freight, modal shift involves truck, rail and ship. Since freight modal shift from road towards rail and shipping is considered infeasible for short distances, as argued by [37] and [38], vans are excluded from modal shift, while for trucks, only long distance demand segments (*NL* and *I*) are assumed to participate. Lastly, aviation is excluded from the modal shift analysis.

2.4. Substitution elasticities

A vast literature is available on transport elasticities, including review studies that provide generic recommended values or “most likely” ranges (as by [39;40]). Transport elasticities measure the responsiveness of a specific transport quantity, such as modal transport demand,

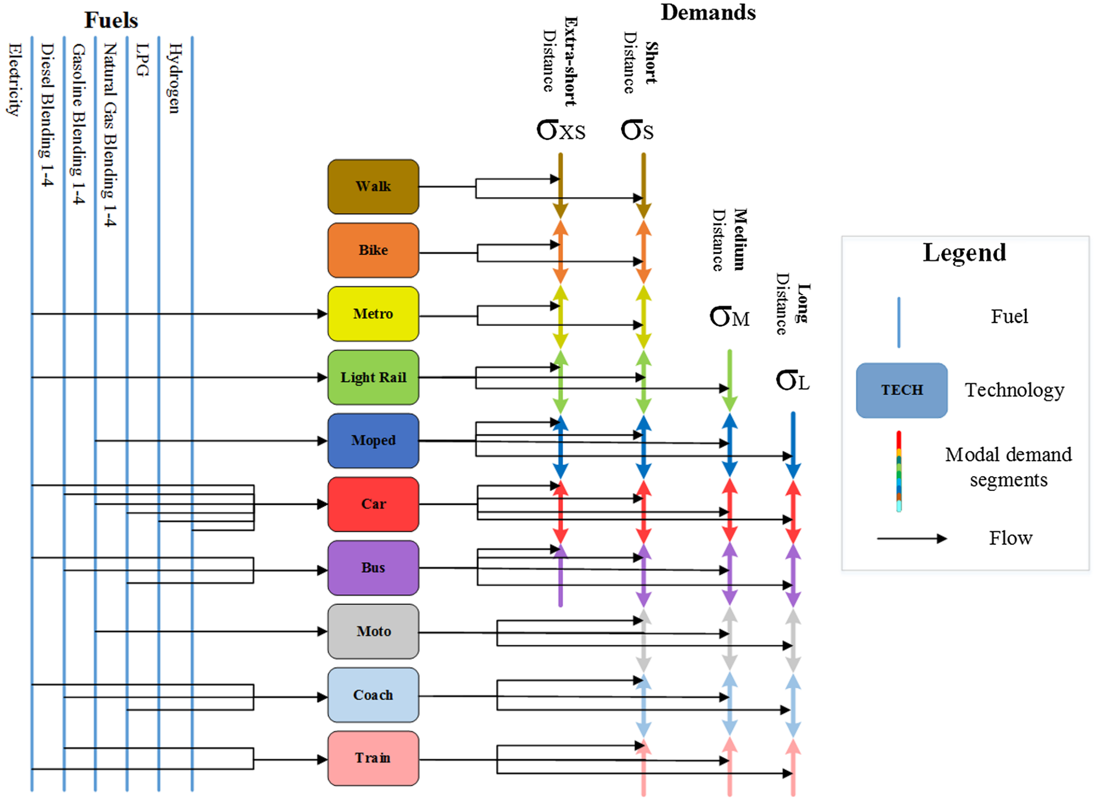


Fig. 2. Inland passenger transport sector in TIMES-Nordic with elastic modal shift. The length of each coloured segment, representing a portion of each distance range class covered by a specific mode, is not representative of the magnitude of the specific modal demand. Modified from [28].

fuel consumption or traffic levels, to changes in other factors, which can range from fuel price to total transport costs, fares etc. [41]. Different methods can be applied to estimate such quantities, such as time series analysis, transport surveys and logit models [42]. Usually elasticities are provided for the short, medium or long terms, generally referring to a response taking place respectively within a year, five years or more [41]. Moreover, where transport modes compete, elasticities can be provided in the form of direct or cross elasticities, depending on whether the responsiveness measured for a certain mode is the result of a change in a transport factor affecting the same mode or another one.

Given the modelling structure adopted to mimic modal shift [28], long-term own-price (or direct) elasticities are identified as the elasticity category suitable for this purpose. TIMES-Nordic covers a forty-year time horizon, broken down into time periods of ten years, where investment decisions are taken with perfect foresight. Thus, modal shift can affect long-term technology investments, making long-term elasticities the preferred category. Moreover, given a specific modal demand, the demand price function coefficient of each step variable involved in the elastic response is computed based on its own modal demand shadow price estimated in the reference case (see [28]). Therefore, even though the new modal demand level is obtained by also taking into account the variations in the other demands composing the aggregate, because of the volume-preserving condition, the main mechanism driving the elastic response represents an own-price elastic response dynamic.

Lastly, in TIMES models a demand shadow price is calculated as the marginal change of the objective function per unit increase in the demand level [32]. Therefore, the shadow price includes all types of cost related to meeting the additional demand unit, potentially covering variable and fixed costs, fuel costs, investment costs etc. Hence, an elasticity representing variation in transport demand (Mpkm or Mtkm, dependent variable) due to a percentage change in the total transport cost (explanatory variable) represents the preferred quantity to adopt in this modelling framework. In light of the available literature, the elasticities assumed for each mode are shown in Table 1. The identified values are similar to those proposed by [43] for use in energy system models, except for the road transport elasticities, which are slightly higher.

For public transport modes (bus, coach, metro, light rail and train) elasticities are assumed on the basis of different literature reviews. Elasticities for bus and coach are based on findings by [39] and [42], for metro and light rail by [42] and for train by [41]. The chosen values fall within the range provided by the different sources for long-term own-price elasticities. Usually, public transport elasticities are provided in the form of modal demand responses due to changes in fares. The chosen elasticities are assumed to be representative of demand responsiveness to changes in total transport costs.

Concerning private modes, long-term own-price elasticities for car demand are calculated based on [44], which provides short-term direct and cross elasticities in terms of mileage responses due to a 10% increase in car transport costs (including operational costs and road pricing). The elasticities are computed with the National Danish Transport model (LTM), a four-stage transport simulation model for Denmark [45]. Transport elasticities are provided by trip purpose and trip

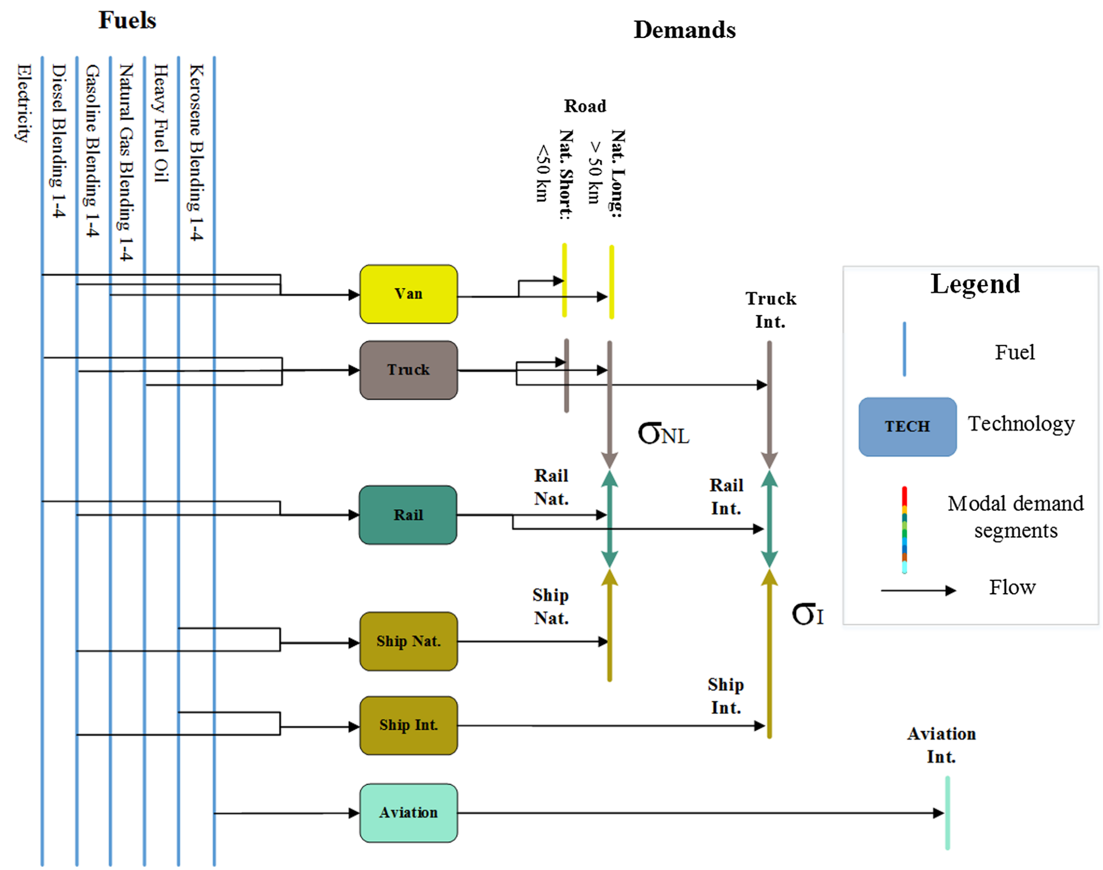


Fig. 3. Freight transport sector in TIMES-Nordic with elastic modal shift. The length of each coloured segment, representing a portion of each distance range class covered by a specific mode, is not representative of the magnitude of the specific modal demand.

Table 1
Long-term own-price elasticities assumed for each transport mode. For references and assumptions refer to the text.

	Mode	Long-term own-price elasticities
Passenger	Bike	−0.58
	Bus	−1.1
	Car	−1.28
	Coach	−1.5
	Light rail	−1.2
	Metro	−0.7
	Moped	−1.28
	Motorbikes	−1.28
	Train	−1.2
	Walk	−0.71
Freight	Rail	−1.2
	Ship	−1.53
	Truck	−1.1

distance. Therefore, a generic short-term direct elasticity for car is calculated as the weighted average of elasticities by trip purpose, using as weights the kilometres travelled for each purpose (also provided by [44]). Since long-term elasticities are usually two to three times larger than short-term ones [41], a long-term elasticity value for car is calculated by scaling up the obtained value by a factor of three.

A similar approach is carried out for walk and bike. However, own-price elasticities imply the existence of a transport cost associated with the mode being analysed, which is not the case for non-motorised modes. Therefore, cross elasticities due to a 10% increase in car costs provided by [44] are adopted as a proxy for direct elasticities. As in the case of car, long-term elasticities are calculated by scaling up the short-term elasticities by a factor of three. For moped and motorbikes the same long-term own-price elasticity is adopted as that used for car.

For every mode, the identified long-term own-price elasticity is assumed to be representative of the distance class k where the highest demand for the selected mode is defined. The characterization of modal elasticity for the other distance categories is achieved in light of the results for car direct elasticities per trip distance provided by [44]. The modal elasticity is calculated for the other aggregates by assuming a progressive 15% decrease or increase respectively for lower and higher distance classes. The only exception is car, whose elasticity in the L class is increased by 30% with respect to its reference distance category (M), in order to make it consistent with findings by [44]. Therefore, the passenger elasticities assumed for longer distances are larger than those for short distances and vice versa, which reflects a general finding in the literature [44].

Concerning the freight sector, long-term own-price elasticities for truck and rail are assumed in light of the "most likely" range of price demand elasticities provided by [40]. The long-term elasticities adopted for truck and rail are respectively −1.1 and −1.2, which fall within the range identified by other literature addressing the same topic as, for example, for truck [46], for rail [47] and for both [48,49]. For ship, an own-price elasticity of −1.53 is assumed based on findings by [48], who provides short-term demand elasticities with respect to transport costs for different freight modes. However, short-term elasticities provided by [48] for truck and rail are similar to long-term elasticities provided by other studies (such as [40]), therefore the identified elasticity for ship is assumed to be valid for the long-term case as well. The assumed long-term own-price elasticities for freight modes are summarised in Table 1.

Freight modal elasticities for each distance category *k* are characterised by adjusting the identified modal elasticities based on distance considerations. In particular, [48] provides freight modal demand elasticities with respect to changes to transport costs for a generic distance and split into short (< 300 km) and long (> 300 km) distances. The relative variation obtained by comparing the generic elasticity with the short- and long- distance elasticities is used to adjust the identified modal elasticity respectively for the *NL* and *I* aggregates. The resulting elasticities for rail and ship are smaller for longer distances, where they are more competitive compared to road transport [37], while an inverse trend is obtained for truck, which is the predominant mode over shorter distances.

Lastly, the modelling set-up adopted to emulate transport modal shift (see previous section or [28]) requires the declaration of a single substitution elasticity for each aggregate *k*. For this reason, σ_k should be representative of the modal demands mix composing the aggregate *k*. A substitution elasticity value for each aggregate is then calculated as the weighted average of the identified modal elasticities using as weights modal demands in 2020. For simplicity, no differentiation across regions is introduced. The resulting σ_k values are shown in Table 2.

2.5. Scenario description

The role of transport modal shift in supporting a low-carbon future transport sector in the Scandinavian region is assessed by comparing the results of two versions of TIMES-Nordic, one equipped with elastic modal shift (TIMES-NordicEMS), the other without (TIMES-Nordic). The two versions of the model are virtually identical, the sole difference being represented by the transport demand structure, as explained in Section 2.3. For TIMES-Nordic, the optimal solution consists in identifying the least-cost portfolios of technologies that fulfil the exogenously provided modal demands, while in TIMES-NordicEMS the optimal solution is identified as a co-optimization of modal shares and technology shares. Thus, modal shift provides TIMES-NordicEMS with additional flexibility when complying with environmental targets or policies.

The two model results are compared for the same “Base” scenario that includes an increasing CO_2 tax, in force from 2020 until the end of the time horizon (2050), and affecting all sectors in the model (see Table 3). The tax levels adopted are based on the marginal abatement costs obtained in the CNS by [6]. Beside the carbon tax, the analysis is performed as a socio-economic optimization, thereby excluding energy taxes and subsidies and other regulatory market mechanisms.

Table 2
Substitution elasticities assumed for each aggregate k. For calculation details and assumptions refer to the text.

	Aggregate (k)	Substitution elasticity (σ_k)
Passenger	XS	−0.82
	S	−1.05
	M	−1.26
	L	−1.59
Freight	NL	−1.66
	I	−1.29

Table 3
CO_2 tax over the studied time period. Based on [6].

Year	2020	2025	2030	2035	2040	2045	2050
2015 €/Tonne of CO_2	6	30	77	92	107	123	130

All the end-use demand projections, including mobility demands, and fuel-market price projections are taken from the CNS assumptions, while expansions in electrical transmission lines are exogenously declared based on the CNS results [6]. Moreover, national domestic potentials for biomass are assumed to be shareable across regions, allowing the model the freedom to consume them where optimal.

Modal shift is allowed only after 2020 with an increasing potential. Following the nomenclature used by [28], a 25% modal shift potential for both the upward and downward directions $\Delta_{k,i}^{up,lo}(t)$ is assumed for each modal demand segment in 2020, rising to 100% in 2050, with linear interpolations for the years in between. The elastic response for each demand is linearized with ten steps (*j*). Concerning the international demand for freight by ships, only the portion of the demand corresponding to trade between Denmark, Norway and Sweden is included in the aggregate *I*. Transport performances due to trade between Norway and Denmark are estimated based on [50], while those due to trade between Sweden and the other two countries are based on [51]. The transport performances obtained for each route are allocated evenly between the two countries, identifying for each region the portion of international maritime freight demand taking place within Scandinavia.

Concerning travel patterns, TPs are relaxed by 5% for all modes from 2012 onwards. In the case of battery electric vehicles (BEVs), the BY TP is assumed to be oriented towards shorter distance range classes compared to internal combustion engine vehicles (ICEVs) in order to emulate the lower autonomy of BEVs, while yearly mileages are assumed to be the same as the ICEVs. However, from 2025 onwards, BEVs are assumed to have the same TPs as ICEVs due to improvements in battery autonomy. Moreover, since the *NS* truck demand does not participate in modal shift, its TP share declared is relaxed by 25% from 2020. In this way, if the other truck demands decrease their levels, the relative share for *NS* is allowed to increase, thus avoiding hindering modal shift.

Lastly, σ_k values are kept constant for all regions and for the whole time horizon. The reference shadow prices are computed in the reference case, which is identical to the Base scenario except that it excludes the CO_2 tax. For more details of the reference case, refer to [28].

3. Results

The potential role of modal shift in reducing CO_2 emission levels in the Scandinavian region is presented in Section 3.1, comparing the results obtained with TIMES-Nordic and TIMES-NordicEMS for the Base scenario. Sections 3.2 and 3.3 present two sensitivity analyses conducted in order to assess the effect on modal shift of, respectively, the adopted substitution elasticity values and the electric car investment costs.

3.1. Role of modal shift in the future Scandinavian transport sector

The modal shares for TIMES-Nordic and TIMES-NordicEMS in 2050 are compared in Fig. 4 for the Base scenario. The overall car demand in the inland passenger sub-sector is 4% lower (about 11,300 Mpkm) in TIMES-NordicEMS compared to TIMES-Nordic. Car is substituted by more efficient modes such as train, metro, light rail and non-motorised modes. In the freight sector, modal shift occurs from truck, the least efficient mode, and, to a lesser extent from ship, to rail, whose demand is 35% higher (about 16,290 Mtkm) in TIMES-NordicEMS.

Concerning the technology fleet of both models, diesel and gasoline

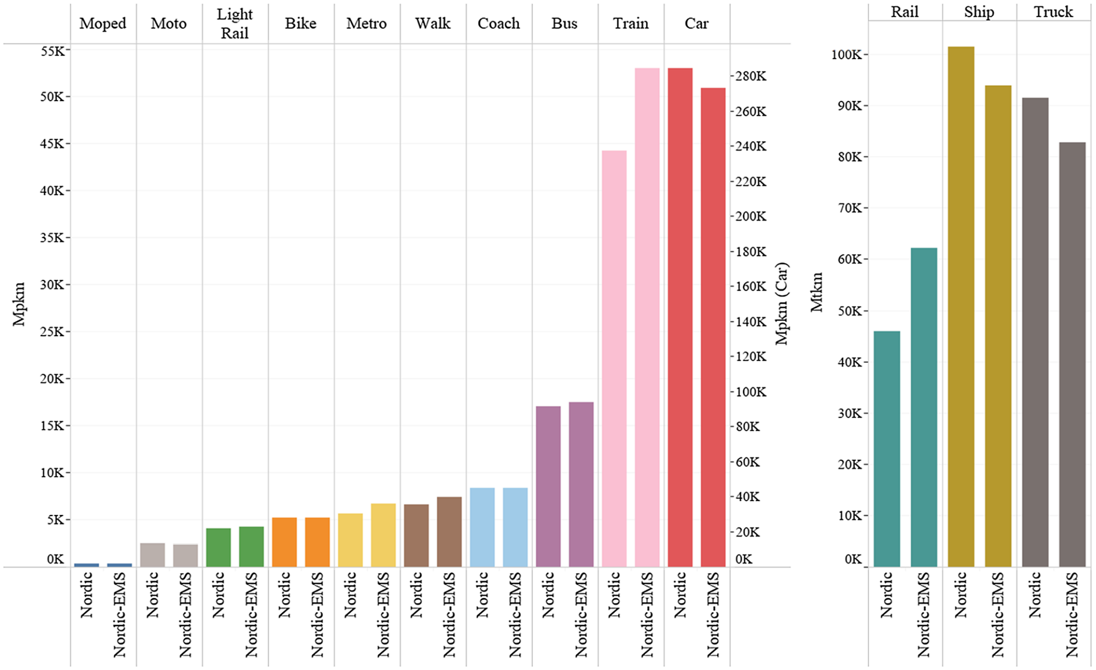


Fig. 4. Comparison of modal shares in 2050 for TIMES-Nordic and TIMES-NordicEMS. Passenger transport is plotted on the left side while freight transport on the right side. For the mode ship, only national demand and the portion of international demand due to the Scandinavian trade are shown.

ICE cars are gradually substituted by natural gas ICE cars and to a lesser extent by battery electric (BE) cars, while gasoline-blended ICE cars (using a blend of gasoline and bio-ethanol) play a transitional role, with penetration peaking in 2030–2040. Diesel ICE buses and coaches are substituted by BEVs on the long run, while diesel-blending ICEVs (using a blend of diesel and bio-diesel) and natural gas ICEVs are adopted as transition alternatives. Passenger and freight rail modes are fully electrified as the existing stocks (including diesel trains) are phased out. Gasoline ICE mopeds and motorbikes are replaced by gasoline-blended ICE 2-wheelers. Diesel ICE trucks are gradually substituted by natural gas ICEVs, while diesel-blending trucks play only a minor role at the beginning of the transition. Diesel and heavy fuel oil freight ships are replaced by flexible fuel ships, which can consume diesel blended with bio-diesel, and heavy fuel oil in variable shares.

Despite the presence of an increasing carbon tax over the time horizon, fossil fuels still play an important role in the end-use sectors in 2050. The fuel consumption of the whole transport sector (excluding aviation) in the Scandinavian region is shown in Fig. 5. For both TIMES-Nordic and TIMES-NordicEMS, fuel consumption slightly falls over the time horizon compared to 2010–2020, despite the assumed increase in mobility demand. This is due to improvements in the fuel economy of new vehicles and the slight electrification of the technology fleet. In particular, for passenger, the assumed growth in mobility demand in 2050 compared to 2010 corresponds to 60% for Denmark and Sweden, and 90% for Norway, while for freight it corresponds to 40% for Denmark and Sweden, and 70% for Norway.

From 2030 onwards fuel consumption differs increasingly between the two model versions. TIMES-NordicEMS presents a lower yearly fuel consumption, accounting in 2050 for almost 26 PJ less than TIMES-Nordic (around −7%). This corresponds to a potential emissions reduction of almost 1.6 Mtonnes of CO_2. For the same period, TIMES-NordicEMS is also characterised by about 2.2% lower cumulative CO_2 emissions in the transport sector compared to TIMES-Nordic, corresponding to almost 30 Mtonnes, most of which is attributable to modal shift. The electricity consumption is slightly higher in TIMES-NordicEMS, though when considering CO_2 emissions related to electricity generation, such differences account for only 0.2 Mtonnes of additional cumulative CO_2 emissions compared to TIMES-Nordic due to the low carbon intensity (CI) of electricity generation (see Appendix B). The lower total system costs in TIMES-NordicEMS compared to TIMES-Nordic (about −0.1%) highlights the cost-effectiveness of modal shift as a measure towards a low-carbon transport sector in Scandinavia.

3.1.1. Modal shift in the inland passenger sector

Fig. 6 shows the inland passenger modal shift for the three Scandinavian countries. The largest contributor to cumulative modal shift over the studied time horizon and for almost every year is Sweden, followed by Denmark and Norway, which present similar contributions. As described by [28], *ceteris paribus*, larger demand segments can vary their levels more than smaller ones. Since Sweden has the greatest inland passenger demands, followed by Denmark and Norway, the same merit order can be found in the sizes of the modal shift. Modal shift presents a similar trend across the different countries: it increases over the years as a result of the increasing CO_2 tax and shift potentials. The

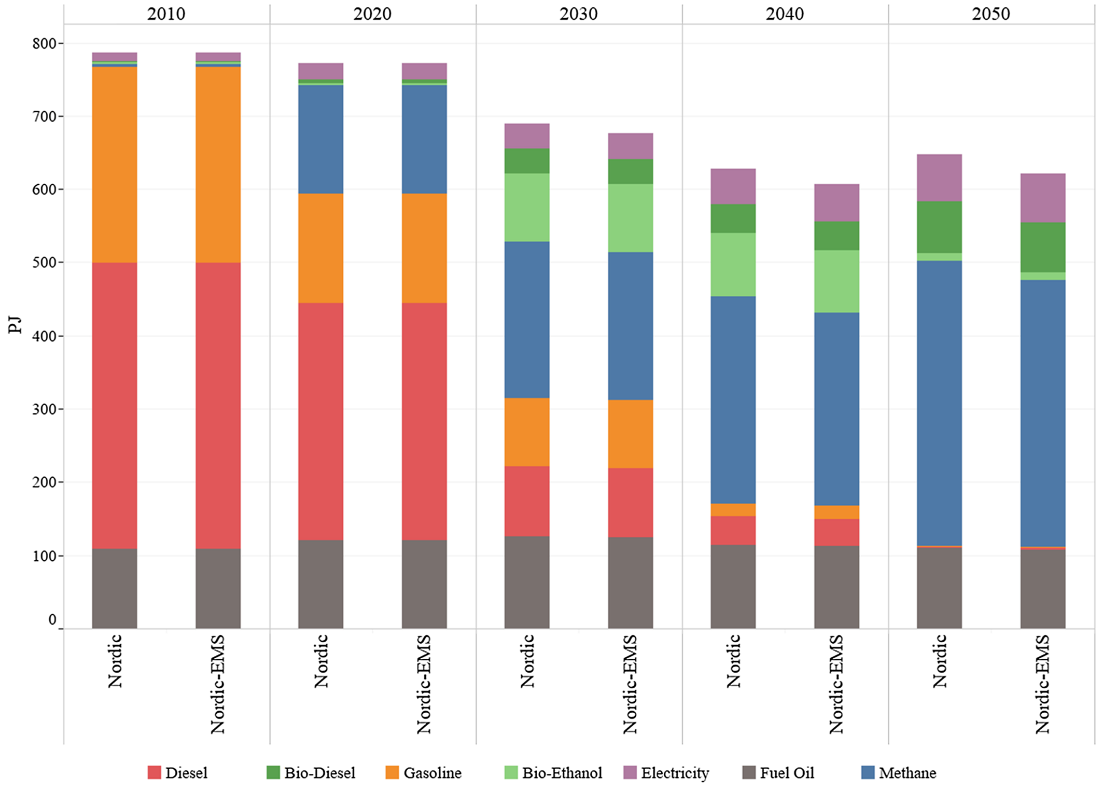


Fig. 5. Fuel consumption in the transport sector for TIMES-Nordic and TIMES-NordicEMS in the Base scenario. Aviation is excluded.

only exception is Denmark, where modal shift in 2050 falls compared to 2040. The reason resides in the reference case, where in 2050, despite the absence of environmental targets and policies, gasoline-blending ICE cars penetrate the Danish transport sector with a high share of bio-ethanol consumption. The bio-ethanol consumed is produced entirely by bio-refineries converting sugar-beet roots. The heat produced by the refining process is also exploited to supply central district heating in Denmark, making bio-ethanol an attractive fuel even where environmental policies are lacking. Bio-ethanol refineries are also installed in Norway and Sweden along the entire time horizon, though bio-ethanol is blended with gasoline at lower percentages. Therefore, in 2050, in the Base scenario, the CO_2 tax causes lower increases in Danish car demands shadow prices with respect to the reference case compared to the other years, resulting in a lower modal shift.

Concerning the different aggregates, in *L* and *M* car is mostly substituted by train, given the orientation of its TP towards longer distances. However, for the *M* aggregate, bus and light rail also contribute slightly to reducing car demand in Sweden and Denmark respectively. Within the *S* category, car is generally substituted by metro, light rail, train and non-motorised modes (walk and bike), while in *XS* it is mainly substituted by metro and non-motorised modes, whose TPs include only shorter distance classes. Bus participates marginally to modal shift in all countries, and it does not follow the same trend (Fig. 6). In Norway and Denmark, bus demand slightly decreases over the time horizon in all distance categories, while in Sweden it decreases only in 2030, increasing in the remainder of the period. The assumed national modal travel patterns, occupancy factors and efficiencies vary slightly across countries due to different travel habits and geographical characteristics. These differences influence mode competition when enabling modal shift. For instance, in Sweden, bus presents a TP oriented more towards longer distances compared to Denmark and Norway (Table A1), while light rail to shorter distances, making bus a more suitable substitute to car, whose demand is generally larger in longer distance classes, especially for Sweden.

3.1.2. Modal shift in the freight sector

Fig. 7 illustrates modal shift in freight in each of the Scandinavian countries for the studied time horizon. The largest share of modal shift takes place in Sweden, followed by Norway and Denmark. Also in this case, the largest freight transport demands are present in Sweden, followed by Norway and Denmark, explaining the merit order of the sizes of modal shift.

The mode rail faces the largest demand growth within the studied time horizon, while accommodating ship and truck demands reductions. In the Base scenario, shadow prices for truck and ship demands tend to increase in all countries and in all years compared to the

Fig. 6. Modal shift in inland passenger transport in the Scandinavian countries obtained with TIMES-NordicEMS in the Base scenario.

reference case due to the CO_2 tax, while for rail they remain almost constant. The reason is that in the reference case freight trains tend to be completely electrified from 2030 onwards. In addition, electricity generation already relies almost entirely on non-fossil sources by 2020 (see Fig. B.1 in Appendix B). Thus, the CO_2 tax does not stimulate large changes in rail demand shadow prices: on the contrary, its demand variations are caused mainly by the volume-preserving condition [28]. Therefore, countries with greater rail demands have a higher modal shift potential due to their greater capacity to absorb the other two freight modes demands. Again, Sweden has the highest transport demands for rail freight, which in 2050 accounts for 39,324 Mtkm, followed by Norway with 6004 Mtkm and Denmark with only 627 Mtkm.

Furthermore, in TIMES-Nordic and TIMES-NordicEMS, modal technical features, such as mileage and average load capacities, are estimated based on aggregated national transport statistics. Thus, for a specific country, they represent an average of a very varied fleet mix. For trucks and ships the calculated technical features are comparable across Scandinavian countries, while rail presents some differences. Rail average load capacities and mileage are almost double in Sweden compared to Norway and triple compared to Denmark. The reason for these differences resides in the composition of the national freight rail sectors, which may include, for example, metal ore trains capable of carrying significant loads, or container trains that carry significantly less. Sweden has the largest mining sector in the Nordics, with fifteen metallic mineral mines. In contrast, Norway accounts for only three mines, while Denmark has no active mines [52]. Moreover, most of the Swedish mining sites are placed in the north, while large industrial sites and harbours are in the south. Therefore, the average technical features estimated for freight trains in Sweden are higher than in the other two countries, increasing the attractiveness of rail compared to other freight modes in the country.

Ship demands mostly fall in all countries over the time horizon, despite the high efficiencies, which for national ships are assumed to be on average 1200 Mtkm/PJ and for international ones almost 6000 Mtkm/PJ. In the model, new freight ships available for investment are limited to consuming heavy fuel oil and a blend of diesel and biodiesel, with increasing shares of maximum blending and improved efficiencies over the years. In the reference case, freight ships consume heavy fuel oil and diesel, while in the Base scenario, some of the diesel is replaced by biodiesel due to the CO_2 tax, resulting in an increase in their demands shadow prices and consequently in a decrease in their demand levels. The only exception is Denmark, where rail freight demands are almost negligible compared to demands for other modes. As a result ship, which represents the second most favourable alternative to trucks, slightly increases its demand levels in every year of the time horizon. The lack of alternative technologies such as gas, ammonia or electric

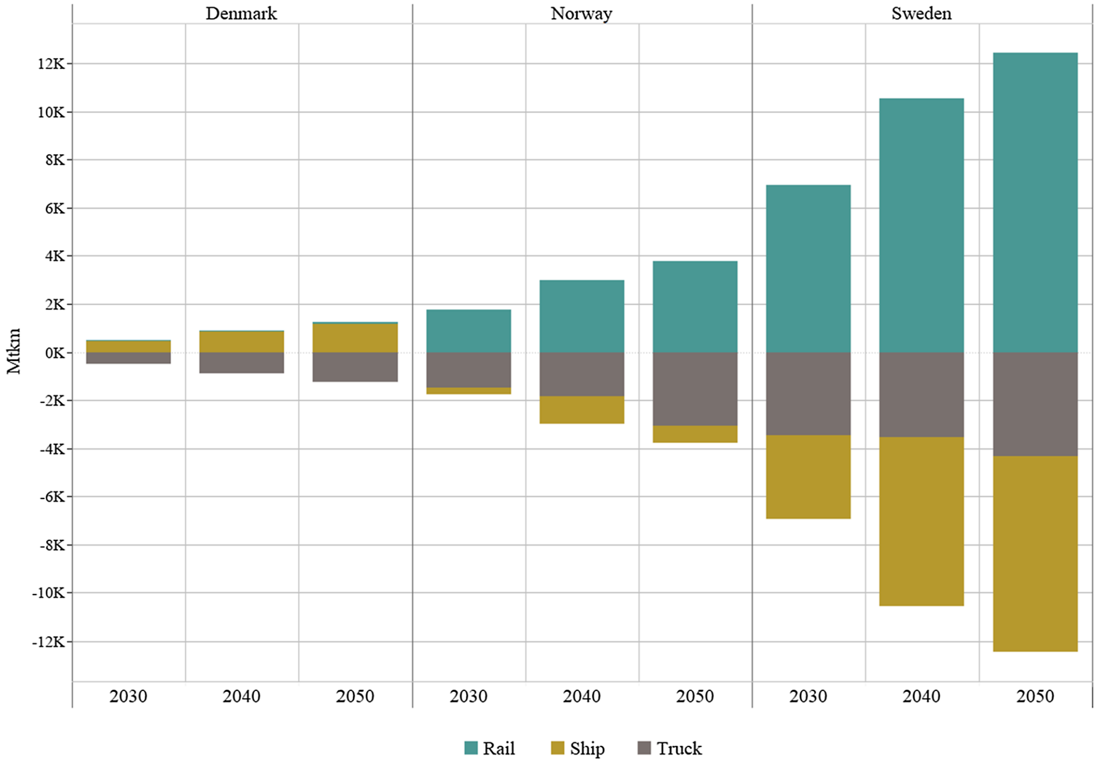


Fig. 7. Modal shift in freight transport in the Scandinavian countries obtained with TIMES-NordicEMS in the Base scenario.

ships is a limitation of this study, whose inclusion could change substantially the potential role of this mode in respect of modal shift in freight transport.

Lastly, freight ships are not constrained in terms of TP, since two independent technologies supply respectively the national and international demands (Section 2.3). Therefore, since TP can hamper the modal shift mechanism [28], this modelling structure favours ship, while penalising truck and rail in terms of modal shift capability. However, this modelling choice aims to differentiate freight ships operating in national or international waters due to substantial technical differences.

3.2. Sensitivity analysis of substitution elasticities

The effect of a variation in the assumed substitution elasticities σ_k on modal shift, is investigated by increasing and decreasing the adopted values for every aggregate k by 10% and 20% for the whole time horizon. The results of the four sensitivity cases, in terms of total modal shift (including all regions) for the passenger and freight sectors, are shown in Fig. 8, including for comparison also the Base scenario.

As expected, in both the passenger and freight sectors, higher substitution elasticities entail larger modal shifts and vice versa. The reason is that adopting higher/lower elasticity values makes the model more/less sensitive to changes in shadow prices [28]. However, passenger modal shift response to elasticity variations shows an almost symmetric trend between the direction of increase and decrease, while freight modal shift responses to increase in elasticity values are lower compared to the decrease cases in 2030 and 2040. Given the modelling assumptions, freight modal shift is already close to saturation point in the Base scenario, to which it tends when increasing the elasticity values. Passenger modal shift still has a margin, resulting in a more linear response. In particular, in 2050, freight modal shift becomes saturated at 27,866 Mtkm, passenger at 51,013 Mpkm, which corresponds to 11,580 Mtkm and 39,715 Mpkm additional demand shift with respect to the Base scenario. The saturation level is identified by increasing σ_k by +2000% compared to the Base scenario for each aggregate k.

3.3. Sensitivity analysis of investment costs for electric cars

This sensitivity analysis evaluates the effect of decreasing the investment costs for electric cars on modal shift. Electric cars are the target of this sensitivity analysis because first, car is the largest contributor to passenger modal shift in the Base scenario. Secondly, given the assumed techno-economic projections for electricity generation technologies, the power sector already come close to achieving carbon neutrality without any policy support in 2020 in the reference case, making EVs a low-carbon technology (refer to Appendix B for more details). Therefore, in cases where electric cars are more competitive

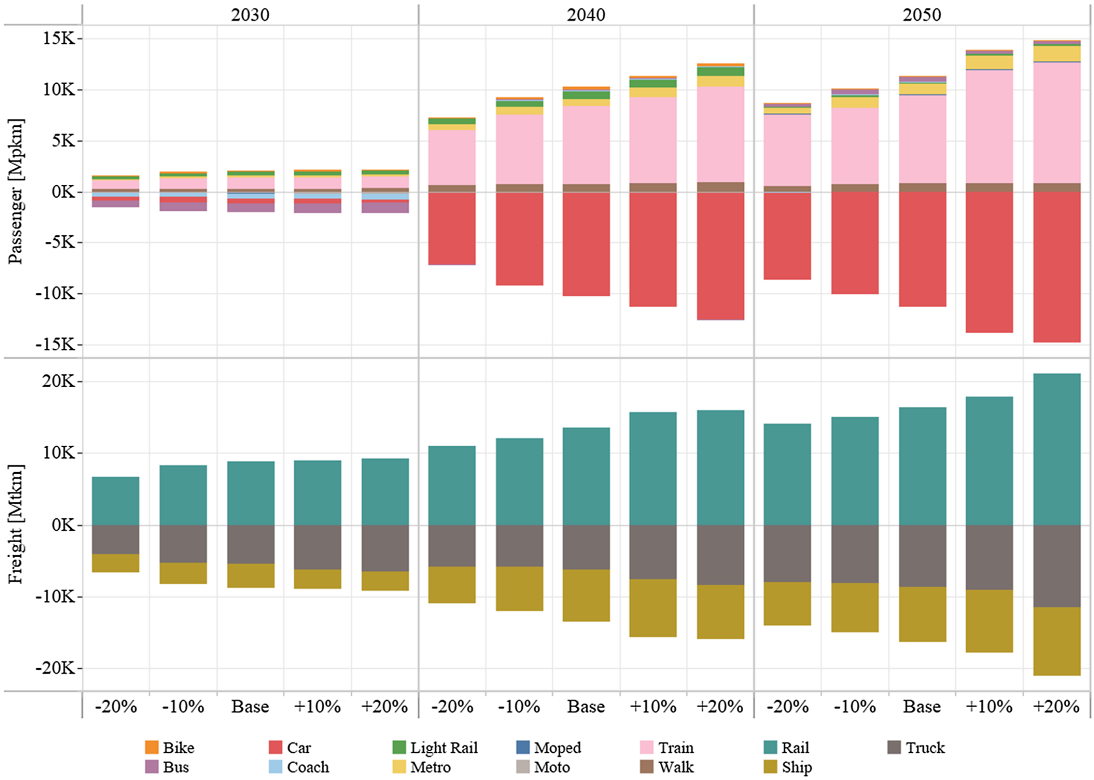


Fig. 8. Comparison of total modal shift over the time horizon in TIMES-NordicEMS, for the Base scenario and the different sensitivity cases, addressing variations in the assumed substitution elasticities σ_k.

than ICE cars, and thus largely already penetrate in the reference case, the CO_2 tax could be ineffective to stimulate variations in car demands shadow prices, resulting in a lower modal shift away from cars.

Investment costs for BE and hybrid electric (HE) cars are reduced progressively by 5%, 10%, 15% and 20% compared to the original values. In Fig. 9, total passenger modal shift over the time horizon for the Scandinavian region is shown for the four sensitivity cases, together with the Base scenario.

As expected, as the investment costs decrease, modal shift tends to decrease too. Decreasing investment costs for BE and HE cars makes them more competitive even in the reference case, where their penetration increases progressively, accounting in 2050 for 9 million and 1.3 million of BE cars respectively in the −20% and −5% cases. A similar trend is followed by HE cars, but to a lesser extent. Thus, the CO_2 tax results in progressively less and less effectiveness in stimulating modal shift away from cars when electric cars are progressively more competitive, regardless of the environmental policies in place. The results suggest that, under specific circumstances, electric cars can be more cost-effective than modal shift in decarbonising passenger transportation. However, this sensitivity analysis involved mainly cost considerations, while other issues linked to dimensions not captured by TIMES-Nordic, such as increased congestion and infrastructure saturation, could hamper the wide penetration of EVs. Therefore, the two phenomena do not necessarily represent mutually exclusive measures, but, as in the middle sensitivity cases (−15% and −10%), they could also act concurrently.

Additionally, in the −20% case, because of the progressive decrease in car demands shadow price variations over the years, car slightly increases its demands in 2040 and 2050. In particular, bus and coach are the modes that face the greatest increases in shadow prices. Train substitutes these modes in the longer distance categories (*L* and *M*), but a substitute is needed for *S* and *XS* to satisfy the volume-preserving condition. One such mode is car, because its demands shadow prices have not changed and also because, since it has the highest demands defined among all passenger modes, it has more freedom to adjust its demand levels while still respecting its TP within the 5% relaxation margin.

4. Discussion and future research

The modal shift levels obtained in this study are comparable to the potentials identified for the Nordic countries by other studies. In the Norwegian freight sector, technical modal shift potential is estimated at between 5 and 7 million tonnes per year [37], which corresponds to

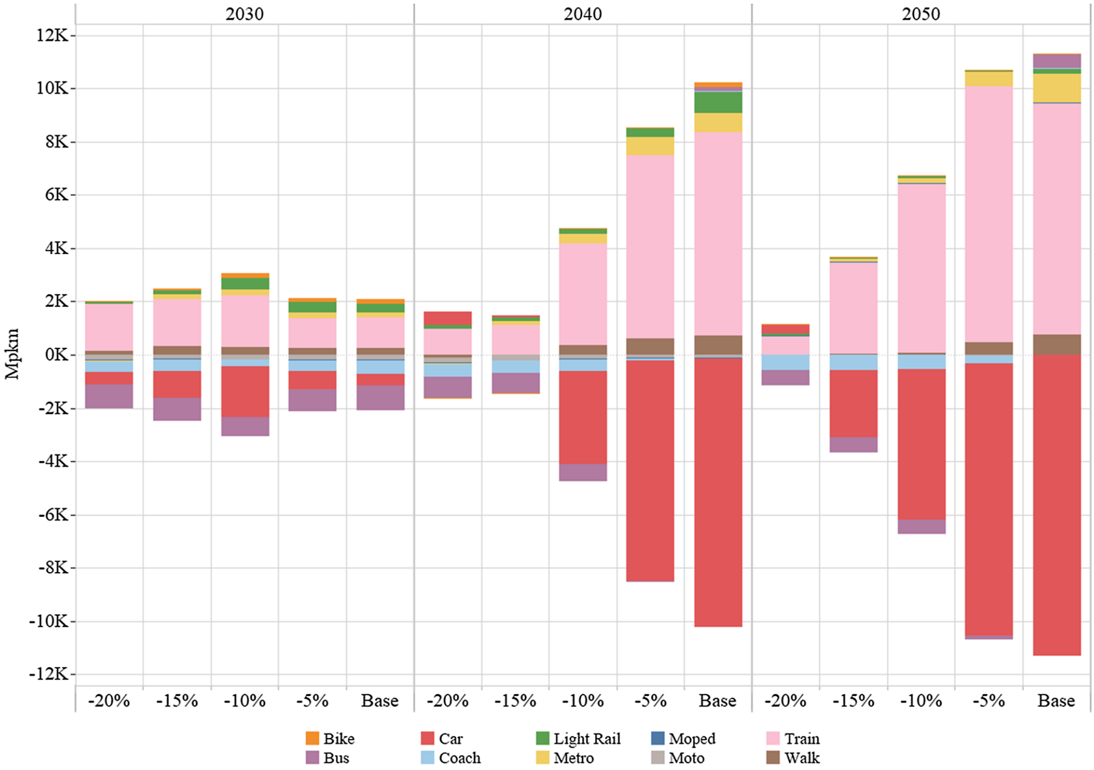


Fig. 9. Comparison of total passenger modal shift over the time horizon in TIMES-NordicEMS for the Base scenario and the different sensitivity cases, addressing progressive decreases in investment costs for electric cars.

2000–2800 Mtkm assuming an average distance of 400 km. The range obtained for Norway across the time horizon (1800–3800 Mtkm) is comparable to this potential. For the inland Danish passenger sector, the total shift obtained in 2050 is around 1300 Mpkm, which is also comparable to the modal shift range obtained by [23] within different scenarios (1000–10,000 Mpkm). However, given the scarcity of studies addressing the same topic and geographical scope, systematic validation is difficult. The use of substitution elasticities, by adopting the values available in the transport literature, represents a compact alternative methodology to modelling transport modal shift in BU optimization energy system models. Incorporating endogenous modal shift enables its potential contribution to a low carbon future energy system to be assessed directly, thus allowing dedicated policy analysis. The simple modelling structure relies to only a minor extent on national travel surveys and does not require the support of external transport simulation models, though the phenomenon addressed is substantially simplified compared to alternative methodologies [28]. Concerning the specific application of this methodology in TIMES-Nordic, the analysis presents some shortcomings, though not ones directly related to the methodology itself.

A well-balanced technological description across transport modes is crucial when introducing modal competition. The inclusion of hydrogen, gas, methanol and ammonia ships could overturn the role of this mode in freight modal shift. The same applies to trucks, whose technological descriptions are limited to diesel-blending and gas ICEVs and BEVs. However, hydrogen and hybrid trucks are also considered promising technologies, especially if accompanied by electrified roads [53]. The inclusion of hydrogen fuel-cell vehicles is particularly attractive given their high fuel economy. In addition, hydrogen could be produced from variable renewable sources via electrolysis when production surpluses occur, representing an additional source of system flexibility and a possible alternative to biofuel imports. This is particularly relevant in the Nordics, where the electricity system already accommodates a major amount of intermittent sources (e.g. wind power) and is expected to accommodate even more of them in the future (see Fig. B.1 in Appendix B). An exhaustive representation of hydrogen fuel-cell vehicles could enrich the scenario analysis with additional insights into the topic.

Moreover, transport infrastructure is not included in the modelling framework, even though, especially for rail, it is considered one possible impediment to modal shift [38]. Elasticity values capture the effect of the existing infrastructure and its availability regarding its responsiveness to transport demand only indirectly and partially. Therefore, when modal shift involves a large variation in modal demands, possibly reaching infrastructure saturation, its direct inclusion in the modelling framework is recommended. Finally, the assumed elasticities derive from transport literature focusing on different countries such as the United Kingdom, Belgium, Denmark, etc. The adoption of specific elasticities valid for the countries under study is recommended.

Concerning further research, for purposes of freight transport modelling, the inclusion of additional modal technologies (such as different freight ships and trains) differentiated in terms of size, load capacity, mileage and typical deployment (type of good transported) together with a characterization of transport demands in terms of good types, could enrich the modal shift analysis. Indeed, different good types have specific requirements/issues related to their delivery, which can range from perishability to safety, technical feasibility such as high load capacity (e.g. ore or crude oil) and others. Capturing these differences in market segmentation in the modelling framework could lead to a more realistic representation of competition between modes when enabling modal shift, rather than simply assuming that each mode is a perfect substitute for the others. On the other hand, this improvement requires profound changes in the modelling structure and extra data.

Lastly, since long-term own-price elasticities are usually provided in the literature for each mode, the possibility to characterise the substitution elasticity in every aggregate *k* per demand segment [36] represents an interesting improvement. In the methodology presented here, a representative substitution elasticity, obtained as weighted average of modal elasticities weighted with their respective demands, is adopted for each aggregate *k* (Section 2.4). The declaration of a substitution elasticity for each demand segment would remove this aggregation step and improve modal representation.

5. Conclusions

In this study, transport modal shift has been modelled in TIMES models (The Integrated MARKAL-EFOM System) using substitution elasticities, adopting, for the first time, transport elasticity values available in the literature for both passenger and freight transport. The methodology is introduced in TIMES-Nordic, the TIMES model describing the entire energy system of Denmark, Norway and Sweden. TIMES-Nordic equipped with elastic modal shift, denominated TIMES-NordicEMS, allows to investigate new decarbonisation pathways for the transport sector, including modal shift as an additional mitigation measure. This study moves a step forward in the representation of transportation in energy system models, enabling the direct assessment of the effectiveness of transport policy mechanisms that are aimed at a low-carbon transition and their interactions with the whole energy system.

The role of modal shift in the decarbonisation of the Scandinavian transport sector is analysed here for the period 2020–2050 by comparing the results of the two model versions with an increasing CO_2 tax. The results show a demand shift towards the more efficient and less carbon-intense modes, increasing over the time horizon due to the increasing tax and shift potentials. In 2050, 11,300 Mpkm of mobility demand shifts from cars towards rail and non-motorised modes, and 16,300 Mtkm from trucks and freight ships towards trains. In particular, freight modal shift reaches levels closer to its saturation with respect to passenger. The inclusion of modal shift entails 26 PJ in lower fuel consumption in 2050 and about 2.2% lower cumulative CO_2 emissions from transport. The additional reduction occurs at a lower total system cost compared to TIMES-Nordic, showing the positive contribution of modal shift in supporting a cost-effective strategy for a Scandinavian decarbonised transport sector. However, a sensitivity analysis of the investment costs of electric cars reveals that a CO_2 tax could be ineffective in stimulating modal shift away from car in a future where such vehicles are more competitive, regardless of the environmental policies in place. The reason is that in Scandinavia the power sector is expected to be already almost carbon neutral by 2030. Therefore, under specific circumstances, electric cars can be more cost-effective than modal shift in decarbonising Scandinavian passenger transportation. However, besides cost considerations, other important aspects, such as transport infrastructure, are not included. As a result, the effect of a wide penetration of electric cars on, for example, congestion cannot be captured.

In addition, comparison of the modal shift obtained with potentials estimated by alternative modelling methods and studies addressing the same topic for the Nordic countries reveals similar results, thus strengthening the validity of the methodology. Despite the simplification of the mechanism regulating modal shift compared to reality, the application of substitution elasticities using elasticities from the transport literature represents a promising and compact methodology for modelling transport modal shift in bottom-up optimization energy system models, as it requires low additional data and modelling efforts. However, when enabling modal shift, the authors suggest to implement a balanced description of technologies across modes to guarantee fair competition. In particular, additional technology options for freight ships and trucks would have improved the completeness of the results presented in this study.

For further research, the authors suggest the identification and adoption of specific substitution elasticities that are valid for the countries under study, as well as the characterization of substitution elasticities per modal demand segment.

Acknowledgments

The work presented in this paper is an outcome of the research activities of the SHIFT (Sustainable Horizons in Future Transport) project (grant number 77892), funded by Nordic Energy Research. The authors are grateful to Tanu Priya Uteng and Inger Beate Hovi from the Institute of Transport Economics (TØI) for their kind and essential support in providing transport data. The authors also thank Julia Hansson from the Swedish Environmental Research Institute (IVL) for her feedback on the analysis.

Appendix A

The appendixes provide additional insights into the assumptions adopted in TIMES-Nordic and the results presented in this article. In particular, Table A1 includes details related to the travel patterns assumed for each mode of transport for the BY in each model region. Appendix B probes electricity generation for the Base scenario and the reference case across the whole time horizon and provides insights regarding CO_2 emissions related to EVs operation.

Table A1
Travel Patterns adopted in TIMES-Nordic for the BY [%] (elaborated based on National Travel survey data: from Sweden [54], Norway [55] and Denmark [56]).

		Region							
		[%]							
Mode	*k*	DKE	DKW	NO1	NO2	SE1	SE2	SE3	SE4
Car	XS	6	6	7	7	5	4	4	4
	S	30	30	32	27	25	22	23	24
	M	22	22	19	19	20	19	22	24
	L	42	42	42	47	50	54	51	48
Battery Electric Cars	XS	10	10	10	10	10	10	10	10
	S	40	40	40	40	40	40	40	40
	M	40	40	40	40	40	40	40	40
	L	10	10	10	10	10	10	10	10
Public Bus	XS	19	19	19	19	7	7	10	7
	S	56	56	56	56	39	39	45	43
	M	16	16	16	16	16	16	27	36
	L	9	9	9	9	38	38	17	14
Coach	S	10	10	10	10	7	7	8	8
	M	10	10	10	10	13	13	15	15
	L	80	80	80	80	80	80	77	77
Motorbike	S	34	34	42	62	16	16	16	16
	M	27	27	23	31	26	26	26	26
	L	39	39	35	7	59	59	59	59
Moped	XS	20	20	13	16	20	20	20	20
	S	67	67	37	52	72	72	72	72
	M	9	9	20	26	7	7	7	7
	L	4	4	30	6	1	1	1	1
Light Rail	XS	7	7	7	7	29	29	29	29
	S	60	60	60	60	70	70	70	70
	M	33	33	33	33	1	1	1	1
Train	S	9	9	9	9	9	9	9	12
	M	20	20	20	20	13	13	14	16
	L	71	71	71	71	78	78	77	72
Metro	XS	37	37	37	37	16	16	16	16
	S	63	63	63	63	84	84	84	84
Bike	XS	58	58	42	56	54	54	47	59
	S	42	42	58	44	46	46	53	41
Walk	XS	93	93	58	60	59	62	67	66
	S	7	7	42	40	41	38	33	34
Truck	NS	6	6	14	13	8	8	8	8
	NL	45	45	71	63	82	82	82	82
	I	49	49	15	24	10	10	10	10
Van	NS	34	34	34	34	34	34	34	34
	NL	66	66	66	66	66	66	66	66
Rail	NL	45	45	68	68	57	67	67	67
	I	55	55	32	32	43	33	33	33

Appendix B

Fig. B.1 presents electricity generation by source across the whole time horizon for the reference case and the Base scenario (obtained with TIMES-NordicEMS). In the Base scenario, CO_2 emissions related to power generation fall steeply up to 2030, accounting for 91% lower levels compared to 2010, then plateau until the end of the time horizon. The residual emissions in the power sector in the Base scenario from 2030 on are generated by waste-incineration cogeneration plants. In the reference case, CO_2 emissions follow a more gradual decreasing trend, accounting in 2050 for an 80% reduction compared to 2010. Due to the absence of any environmental policies in the reference case, coal cogeneration plants are still present in the system, resulting in higher emissions compared to the Base scenario.

The share of electricity generation in both the Base scenario and the reference case is dominated by renewables (hydro, offshore wind, onshore wind and solar PV), which account for 65% of total electricity produced in 2010, and 97% and 99% in 2050 respectively for the reference case and the Base scenario. Sweden's nuclear plants are responsible for 19% of Scandinavian electricity generation in 2010, however, their share decreases gradually over time before disappearing in 2050 in both the Base scenario and the reference case. Fossil-fuel plants (natural gas, coal and oil) cover 15% of power production in 2010 before falling over the time horizon until they account for only 1% of market share in the reference case in 2050, while already disappearing in the Base scenario by 2030. It is worth noticing that the overall electricity produced in the Base scenario after 2030 is slightly higher than in the reference case (around 4% in 2050), this being caused by a higher degree of electrification in the end-use sectors, such as transportation. The additional electricity generation is mainly covered by onshore and offshore wind. Lastly, power plants equipped with carbon capture storage are not included in the scenario analysis presented in this paper.

The carbon intensity (CI) of electricity generation calculated in 2010 for the whole Scandinavian region is around 34 $KgCO_2/GJ$ (considering only

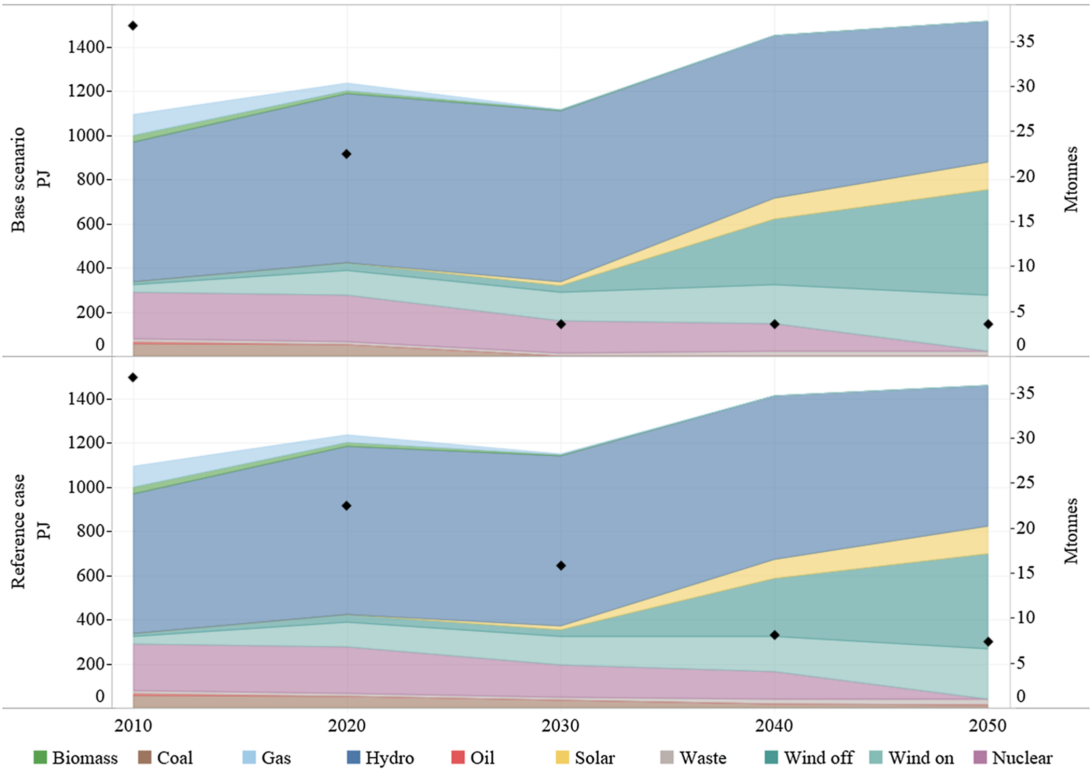


Fig. B1. Electricity generation by source (area graph, left axis) and associated CO_2 emissions (scatter graph, right axis) in the Base scenario and the reference case. For the Base scenario, results are obtained with TIMES-NordicEMS. The same trends are observed with TIMES-Nordic.

the fuel combustion at the plants). When including also transmission and distribution losses (~8%), CI of electricity consumption in the transport sector reaches 37 $KgCO_2/GJ$, which is already substantially lower respect to gasoline, diesel and natural gas CI, which are assumed respectively to be 69, 74 and 56 $KgCO_2/GJ$.

Despite the upstream emissions related to the production of the fuels not being included in TIMES-Nordic, the higher carbon intensities of gasoline, diesel and natural gas compared to electricity, and the lower fuel economy of ICEVs compared to EVs, makes EVs low-carbon alternatives to ICEVs in both the Base scenario and the reference case. Obviously, the electricity CI varies by country since the electricity generation mix differs across the Scandinavian countries. However, the strong reduction in emissions in the power sector after 2020 makes EVs perform better in terms of CO_2 emissions related to the operation of the vehicle compared to ICEVs in every Scandinavian country.

References

[1] Sims R, Schaeffer R, Creutzig F, Cruz-Núñez X, D'Agosto M, Dimitriu D, et al. Transport climate change 2014: mitigation of climate change. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, editors. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2014.

[2] International Energy Agency. Energy technology perspectives 2015. Paris, France; 2015.

[3] Nordic Action Group on Climate and Energy. Nordic transport ways. Stockholm, Sweden;2015.

[4] International Transport Forum. Transport CO2 and Paris agreement reviewing the impact of nationally determined contributions. Paris, France; 2018.

[5] International Energy Agency. World energy outlook 2018. Paris, France; 2018.

[6] International Energy Agency, Nordic Energy Research. Nordic Energy Technology Perspectives 2016. Paris, France. Oslo, Norway; 2016.

[7] International Energy Agency. Nordic EV outlook 2018. Paris, France; 2018.

[8] Tattini J, Mulholland E, Venturini G, Ahancian M, Gargiulo M, Balyk O. A long-term strategy to decarbonise the Danish Inland passenger transport sector. In: Giannakidis G, Karlsson K, Labriet M, Gallachóir BÓ, editors. Limiting global warming to well below 2 °C: energy system modelling policy development. Lect. Notes Energy, vol. 64, Springer; 2018. p. 137–53. doi: 10.1007/978-3-319-74424-7_9.

[9] Rosenberg E, Fidje A, Espegren KA, Stiller C, Svensson AM, Møller-Holst S. Market penetration analysis of hydrogen vehicles in Norwegian passenger transport towards 2050. Int J Hydrogen Energy 2010;35:7267–79. https://doi.org/10.1016/j.ijhydene.2010.04.153.

[10] Krook-Riekkola A, Sandberg E. Net-zero CO2-emission pathways for sweden by cost-efficient use of forestry residues. In: Giannakidis G, Karlsson K, Labriet M, Gallachóir BÓ, editors. Limiting global warming to well below 2 °C: energy system modelling policy development. Lect. Notes Energy, vol. 64, Springer Verlag; 2018. p. 123–36. doi: 10.1007/978-3-319-74424-7_8.

[11] Börjesson M, Ahlgren EO, Lundmark R, Athanassiadis D. Biofuel futures in road transport – a modeling analysis for Sweden. Transp Res Part D Transp Environ 2014;32:239–52. https://doi.org/10.1016/j.trd.2014.08.002.

[12] International Energy Agency, Nordic Energy Research. Nordic Energy Technology Perspectives 2013. Paris, France. Oslo, Norway; 2013.

[13] Pursiheimo E, Holttinen H, Koljonen T. Path toward 100% renewable energy future and feasibility of power-to-gas technology in Nordic countries. IET Renew Power Gener 2017;11:1695–706. https://doi.org/10.1049/iet-rpg.2017.0021.

[14] Seljom P, Rosenberg E. A scandinavian transition towards a carbon-neutral energy system. In: Giannakidis G, Karlsson K, Labriet M, Gallachóir B, editors. Limiting

Global warming to well below 2 °C energy system modelling policy development lect. Notes Energy, vol. 64, Springer; 2018. p. 105–21. doi: 10.1007/978-3-319-74424-7_7.

[15] Juul N, Meibom P. Road transport and power system scenarios for Northern Europe in 2030. Appl Energy 2012;92:573–82. https://doi.org/10.1016/j.apenergy.2011.11.074.

[16] Taljegard M, Göransson L, Odenberger M, Johnsson F. Impacts of electric vehicles on the electricity generation portfolio – a Scandinavian-German case study. Appl Energy 2019;235:1637–50. https://doi.org/10.1016/j.apenergy.2018.10.133.

[17] Norden. Energy and Transport. Key results and recommendations. Copenhagen, Denmark; 2014.

[18] Schäfer A. Introducing behavioral change in transportation into energy/economy/environment models. Policy research working paper no. WPS 6234. Washington, DC: World Bank; 2012.

[19] Venturini G, Tattini J, Mulholland E, Gallachóir BÓ. Improvements in the representation of behaviour in integrated energy and transport models. Int J Sust Transp 2018. https://doi.org/10.1080/15568318.2018.1466220.

[20] International Energy Agency. Transport energy and CO2. Paris, France; 2009.

[21] International Energy Agency. Energy technology perspectives 2014. Paris, France; 2014.

[22] European Commission. White Paper. Roadmap to a single European transport area – towards a competitive and resource efficient transport system. Brussels, Belgium; 2011.

[23] Tattini J, Gargiulo M, Karlsson K. Reaching carbon neutral transport sector in Denmark – evidence from the incorporation of modal shift into the TIMES energy system modeling framework. Energy Pol 2018;113:571–83. https://doi.org/10.1016/j.enpol.2017.11.013.

[24] Daly H, Ramea K, Chiodi A, Yeh S, Gargiulo M, Gallachóir BPÓ. Incorporating travel behaviour and travel time into TIMES energy system models. Appl Energy 2014;135:429–39. https://doi.org/10.1016/j.apenergy.2014.08.051.

[25] Pye S, Daly H. Modelling sustainable urban travel in a whole systems energy model. Appl Energy 2015;159:97–107. https://doi.org/10.1016/j.apenergy.2015.08.127.

[26] Cayla J-M, Maïzi N. Integrating household behavior and heterogeneity into the TIMES-Households model. Appl Energy 2015;139:56–67. https://doi.org/10.1016/j.apenergy.2014.11.015.

[27] Tattini J, Ramea K, Gargiulo M, Yang C, Mulholland E, Yeh S, et al. Improving the representation of modal choice into bottom-up optimization energy system models – the MoCho-TIMES model. Appl Energy 2018;212:265–82. https://doi.org/10.1016/j.apenergy.2017.12.050.

[28] Salvucci R, Tattini J, Gargiulo M, Lehtilä A, Karlsson K. Modelling transport modal shift in TIMES models through elasticities of substitution. Appl Energy 2018;232:740–51. https://doi.org/10.1016/j.apenergy.2018.09.083.

[29] International Energy Agency. ETSAP – energy technology systems analysis programme n.d. < https://iea-etsap.org/ > [accessed November 20, 2018].

[30] Lind A, Espegren K. The use of energy system models for analysing the transition to low-carbon cities – the case of Oslo. Energy Strateg Rev 2017;15:44–56. https://doi.org/10.1016/j.esr.2017.01.001.

[31] Føyn THY, Karlsson K, Balyk O, Grohnheit PE. A global renewable energy system: a modelling exercise in ETSAP/TIAM. Appl Energy 2011;88:526–34. https://doi.org/10.1016/j.apenergy.2010.05.003.

[32] Loulou R, Goldstein G, Kanudia A, Lehtilä A, Remme U. Documentation for the TIMES Model – Part I: TIMES concepts and theory. Energy systems technology analysis programme (ETSAP); 2016. < https://ieaetsap.org/docs/Documentation_for_the_TIMES_Model-Part-I_July-2016.pdf > [accessed October 5, 2018].

[33] Balyk O, Andersen KS, Dockweiler S, Gargiulo M, Karlsson K, Næraa R, et al. TIMES-DK: technology-rich multi-sectoral optimisation model of the Danish energy system. Energy Strateg Rev 2019;23:13–22. https://doi.org/10.1016/j.esr.2018.11.003.

[34] Wikipedia. Electricity price area; 2018. < https://en.wikipedia.org/wiki/Electricity_price_area > [accessed October 9, 2018].

[35] Eurostat. Energy balances; 2018. < https://ec.europa.eu/eurostat/web/energy/data/energy-balances > [accessed December 1, 2018].

[36] Lehtilä A. TIMES Micro – elastic demand functions. Energy systems technology analysis programme (ETSAP). International energy agency (IEA); 2018. < https://ieaetsap.org/docs/TIMES-Micro-Note.pdf > [accessed July 5, 2018].

[37] Nordic Council of Ministers (Norden). Reducing CO2 Emissions from Freight. Copenhagen, Denmark; 2018.

[38] The Swedish National Road and Transport Research Institute. Vierth I, Mellin A. Svensk godsstudie baserad på nationell och internationell litteratur Internationell exposé-persontransporter. Linköping, Sweden; 2008.

[39] RAND Corporation. Dunkerley F, Wardman M, Rohr C, Fearnley N. Bus fare and journey time elasticities and diversion factors for all modes. Cambridge, UK; 2018.

[40] Oum TH, Waters WG, Yong JS. A survey of recent estimates of price elasticities of demand for transport. Washington; 1990.

[41] Victoria Transport Policy Institute. Litman TA. Understanding transport demands and elasticities: how prices and other factors affect travel behavior. Canada; 2017.

[42] Transport Research Laborratory. Balcombe R, Mackett R, Paulley N, Preston J, Shires J, Titheridge H, et al. The demand for public transport: a practical guide. Workingham, UK; 2004.

[43] Pye S, Usher W, Strachan N. The uncertain but critical role of demand reduction in meeting long-term energy decarbonisation targets. Energy Pol 2014;73:575–86. https://doi.org/10.1016/j.enpol.2014.05.025.

[44] Rich J. The weekday demand model in LTM – model for generation, destination and mode choice. Kgs. Lyngby, Denmark; 2015.

[45] DTU Transport. Landstrafikmodellen; 2018. < http://www.landstrafikmodellen.dk/ > [accessed October 5, 2018].

[46] De Jong G, Schroten A, Van Essen H, Otten M, Bucci P. The price sensitivity of road freight transport – a review of elasticities. The Hague, Netherlands; 2010.

[47] The Swedish National Road and Transport Research Institute. Vierth I, Mellin A, Hylén B, De Jong G, Bucci P. Priselasticiteter som underlag för konsekvensanalyser av förändrade banavgifter för godstransporter. Linköping, Sweden; 2010.

[48] Beuthe M, Jourquin B, Geerts JF, À Ndjang'Ha C Koul. Freight transportation demand elasticities: a geographic multimodal transportation network analysis. Transp Res Part E Logist Transp Rev 2001;37:253–66. https://doi.org/10.1016/S1366-5545(00)00022-3.

[49] Abdelwahab WM. Elasticities of mode choice probabilities and market elasticities of demand: evidence from a simultaneous mode choice/shipment size freight transport model. Transp Res Part E, Logist Transp Rev 1998;34:257–66.

[50] Brahim TS ben. Future marine fuels – a Danish case study on climate compatible energy pathways. Europa-Universität Flensburg, Germany; 2018.

[51] Transport Analysis. Maritime transport, shipping goods statistics; 2018. < https://www.trafa.se > [accessed August 20, 2018].

[52] Nordic Council of Ministers (Norden). Mining in the Nordic Countries. Copenhagen, Denmark; 2015.

[53] International Energy Agency. The future of trucks – implications for energy and the environment. Paris, France; 2017.

[54] Transport Analysis. Swedish National Travel Survey – dataset 2011-2016; 2018. < https://www.trafa.se > [accessed March 4, 2018].

[55] Norwegian Centre for Research Data (NSD). Norwegian National travel Survey – dataset 2013/2014; 2014. < http://www.nsd.uib.no > [accessed May 12, 2017].

[56] DTU Transport. Danish National Travel Survey – dataset TU0615v1 from May 2006 to December 2015; 2016 [accessed September 10, 2017].

Glossary

BE: Battery Electric
BEVs: Battery Electric Vehicles
BU: Bottom-Up
BY: Base year
CI: Carbon Intensity
CNS: Carbon Neutral Scenario
CO_2: Carbon Dioxide
DKE: Denmark East
DKW: Denmark West
E4: Energy-economy-environment-engineering
ETP: Energy Technology Perspectives
ETSAP: Energy Technology Systems Analysis Program
EVs: Electric Vehicles
HE: Hybrid Electric
I: International
ICE: Internal Combustion Engine
ICEV: Internal Combustion Engine Vehicle
IEA: International Energy Agency
L: Long distance
LTM: Landstrafikmodellen, Danish National Transport Model
M: Medium distance
NETP: Nordic Energy Technology Perspectives
NL: National Long Distance
NO1: Norway South
NO2: Norway North
NS: National Short Distance
Pkm: Passenger-kilometer
S: Short distance
SE1: Sweden Nord Pool bidding area 1
SE2: Sweden Nord Pool bidding area 2
SE3: Sweden Nord Pool bidding area 3
SE4: Sweden Nord Pool bidding area 4
TIMES: The Integrated MARKAL-EFOM System
TIMES-DK: TIMES model of Denmark
TIMES-Nordic: TIMES model of the Scandinavian region
TIMES-NordicEMS: TIMES model of the Scandinavian region with Elastic Modal shift
Tkm: Tonne-kilometer
TP: Travel Pattern
XS: Extra short distance